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Self-Fixturing Architecture

Darin C. Russell

University of Nebraska-Lincoln, drussell@huskers.unl.edu

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SELF-FIXTURING ARCHITECTURE

Darin Russell

A Design Thesis
Presented to the Faculty of
The College of Architecture at
the University of Nebraska

In Partial Fulfillment of
Requirements for the Degree
of Master of Architecture

Major: Architecture

Under the Supervision of
Professor Steve Hardy

Lincoln, Nebraska

May, 2012

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Note regarding chronology:

The thesis process constantly moved back and forth among different scales. For example, development on a scale 0 connection lead to scale 1 assemblies, and experimentation with scale 1 assemblies in turn lead to the implicit creation of new scale 0 connections, etcetera. Given the importance of scale within the pragmatically driven realm of manufacturing, it has been selected as a means to organize the design research of the thesis. Hence, the contents of this book are non-chronological and instead governed by the notion that as the scale of manufactured architecture increases, so does the complexity and amount of information that it is built upon.

Thesis Statement

Fixture - device used to hold and/or position a part or parts within an assembly (Jig and Fixture Design)

"Fixturing" as a concept and practice is applied almost exclusively to manufacturing. Mass production utilizes the fixture to assemble volumes of identical parts into volumes of identical assemblies via holding and locating. This results in accurate and repeatable assembly of parts. Typically, the fixture is only economical when a large enough volume of assemblies exist - a small number of assemblies does not warrant the design and fabrication of a fixture. In this context, the fixture is external from the assembly - that is, the parts do not intrinsically locate and hold themselves within the assembly. It is arguably more cost effective to develop one external fixture and then produce simple parts for use within the fixture. This is suitable for mass production of identical products.

The conventional alternative to mass production is hand production, where each product is variable. Architecture tends to fall more into this category - buildings are more unique and variable in terms of accuracy, repeatability, and specificity. Complexity no doubt factors into this, though mass production can also yield complex products. Digital fabrication offers the potential to economically realize higher variability without the expense of highly skilled hand production. The fixture could further improve economy (and precision) as it removes the need for highly skilled assembly. Given the fact that architecture is usually non-uniform, eternal fixtures are not reasonable. However, if digital fabrication is being utilized to create unique parts, it is reasonable to embed fixturing properties within the parts. Thus, digitally-fabricated self-fixturing parts can be expediently assembled to create unique works of architecture.

Self-fixturing architecture exists between the super-specialized "one-off" and the super-generalized module. The proposed implementation of self-fixturing is to first explore fixturing on different scales. The scales

are loosely defined as Scale 0 (a single joint), Scale 1 (an assembly of parts to make a structural member, such as a beam, or a bench), Scale 2 (an assembly of members), and Scale 4 (an entire building).

The gas station has been selected as a typology for a number of reasons, though the intent of the thesis is not exclusively to explore architectural aspects of this typology but to rather explore how fixturing can exist within the typology. The gas station gives a degree of specificity to the design, resulting in a genotype. The genotype is parametrically controlled such that a specific site can inform the parameters in order to create an architectural solution. Moderate span lengths also permits the use of conventional laser cutting beds. The gas station is favorable as a typology given its status as a semi-mass-produced entity, lending itself to "specified mass production." It is a ubiquitous building type that demands economy, yet could benefit from a higher degree of design consideration.

This thesis, on one level, attempts to inject beauty into the utilitarian. Beauty is of course subjective, but here it is about the "manu-tech" aesthetic, where the process of making is evident in the design, and the parametric flexibility of the genotype allows conformation to site conditions and human needs.

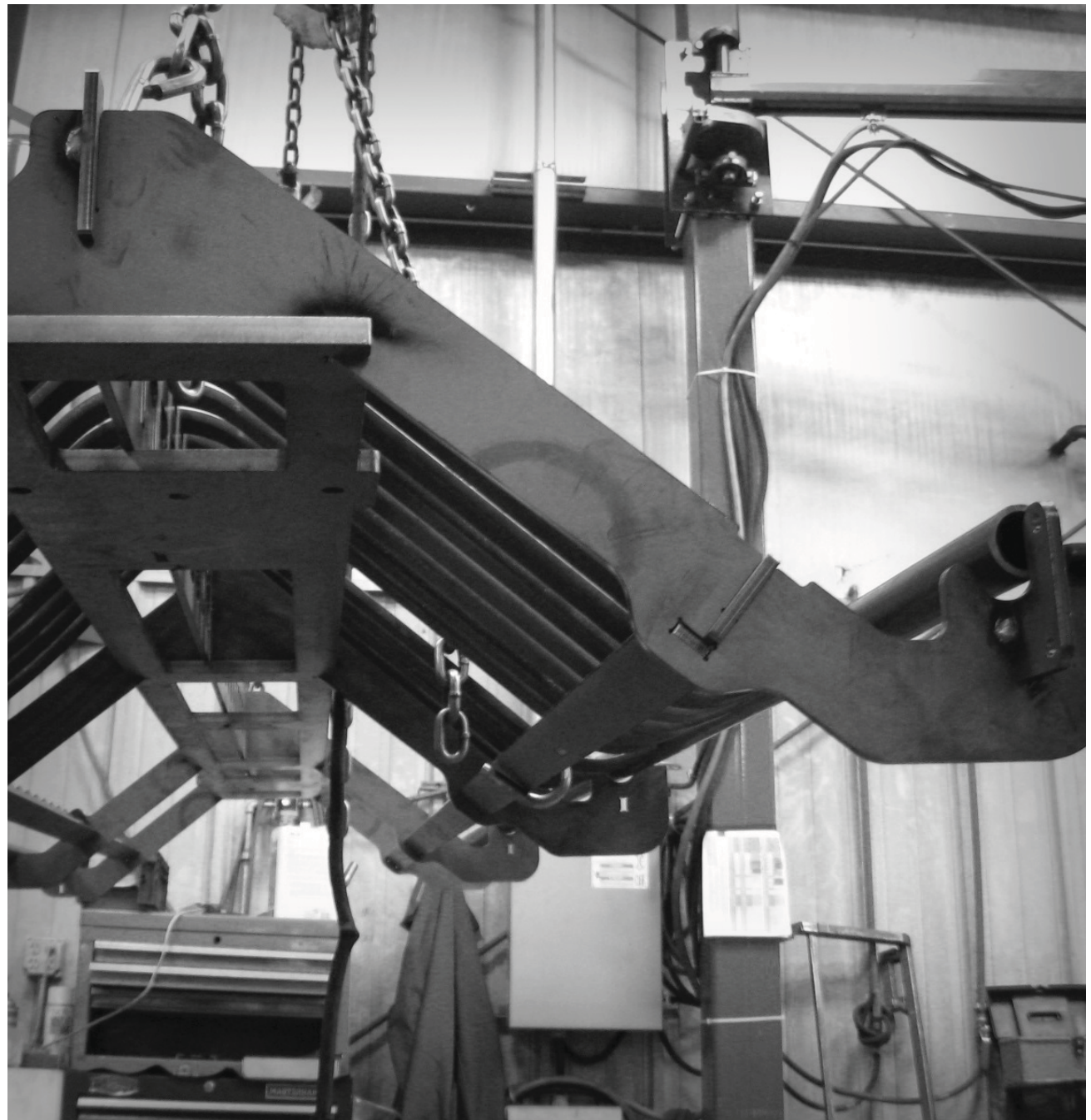
A prominent aspect of the thesis is the idea of designing from the detail up. "The aesthetic of parametricism" can be criticized for its disregard of fabrication and economy. "Parametricism" is not representative of all realms of parametric thinking. A system of details can be resolved with parametric control. This system of details yields a complex yet flexible genotype that can gain specificity given its parametric control.

Fixture

Experience at TMCO serves to inform the methodologies of the thesis. TMCO is a steel manufacturing company located in Lincoln, Nebraska. Fixtures are an essential part of the welding process that occurs in the production of assemblies at TMCO. There are two types of welding fixtures employed within the welding environment: assembly fixtures and holding fixtures. Assembly fixtures hold and locate parts in the assembly configuration such that the parts can be welded to each other. In some cases, these parts are only tack welded in place, and then placed in a holding fixture, which serves to hold the tacked assembly in a repeatable position such that it can be fully welded with a robotic welding arm.

It is interesting to note that the welding fixtures shown as a part of this thesis are external fixtures, yet are composed of self-fixturing parts. This results from the fact that TMCO utilizes digital fabrication to produce most of its parts, meaning that self-fixturing properties are fairly easy to add to the parts that compose a fixture. Additionally, fixtures need to maintain the required tolerance of the assembly they are producing. Given this, fixtures themselves require high precision assembly. Self-fixturing facilitates the production of an accurate fixture.

In order to appreciate the fixture's role in manufacturing (and architecture), it is helpful to understand the nature of the assembly.

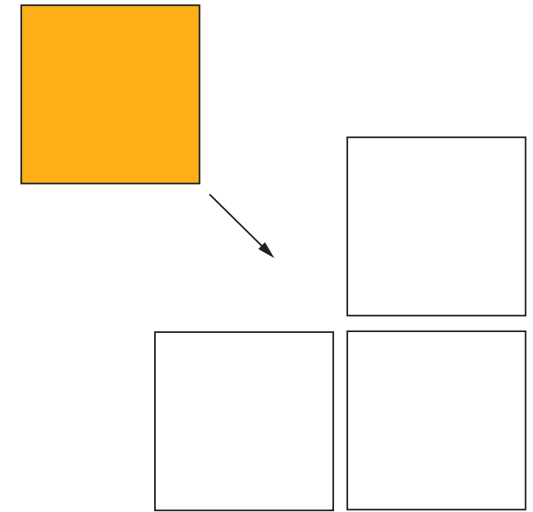
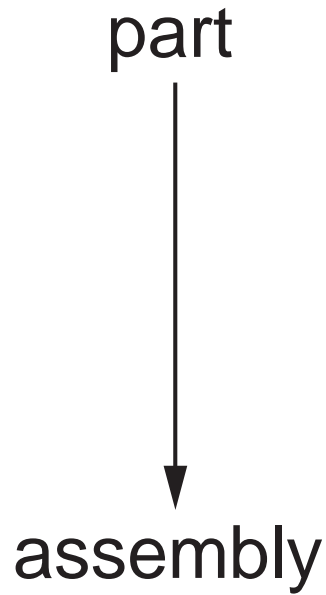


Welding fixture

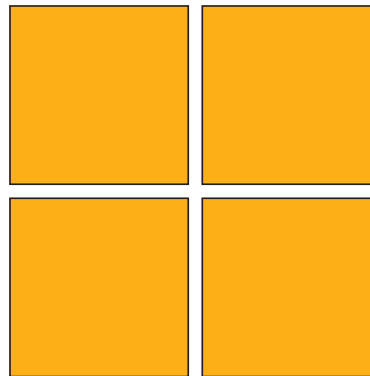
Assembly

The part/assembly relationship is necessary within design of the built environment for a number of reasons.

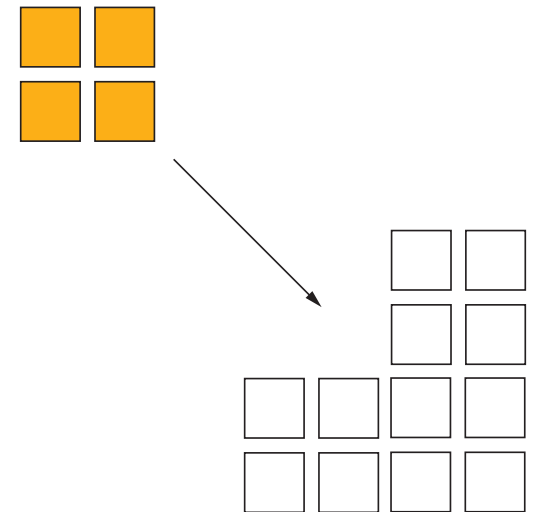
1. Large assemblies can be transported as smaller parts.
Manufacturing rarely occurs exclusively in the same geographic region as the point of consumption.
2. An assembly can be composed of parts with diverse materials.
3. Parts can allow motion when desired.
4. Interchangeability.
5. Efficiency and mass reduction.
For example, it is much more efficient to fabricate an open-web joist using multiple parts as opposed to machining or casting a single continuous part.



Part consumed by (sub) assembly



(Sub) assembly



(Sub) assembly consumed by (super) assembly

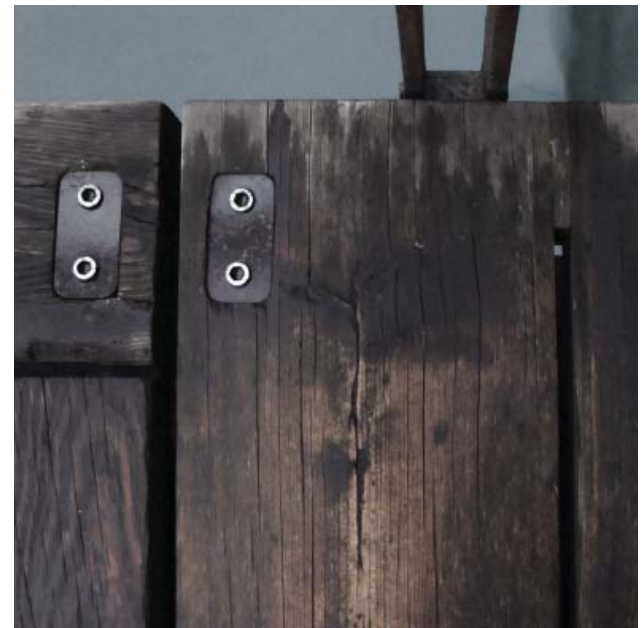
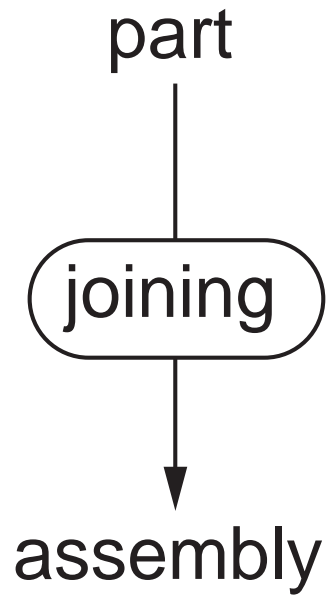
Joining

Joining is the process through which parts become assemblies. There are three fundamental types of joining.

Mechanical joining

Adhesive bonding

Welding



Bolted connection



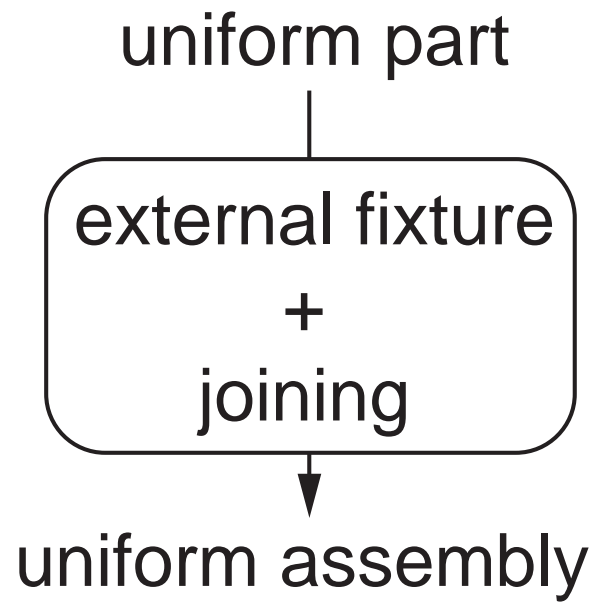
Welded connection



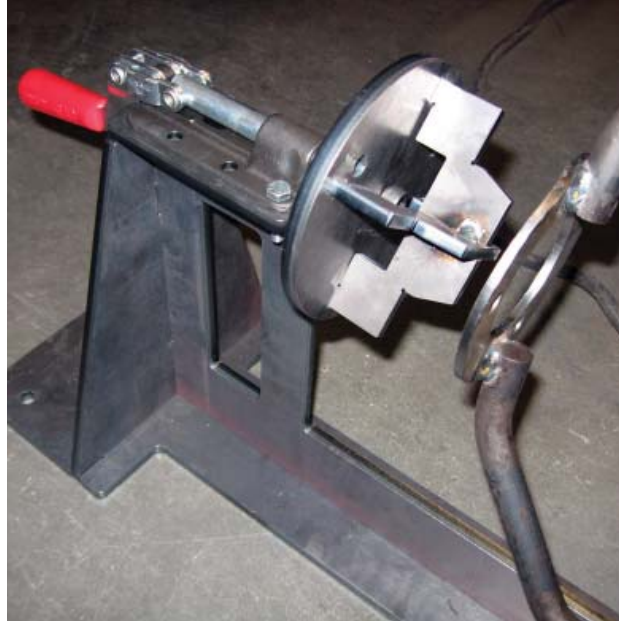
Adhesive connection

Mass Fixturing

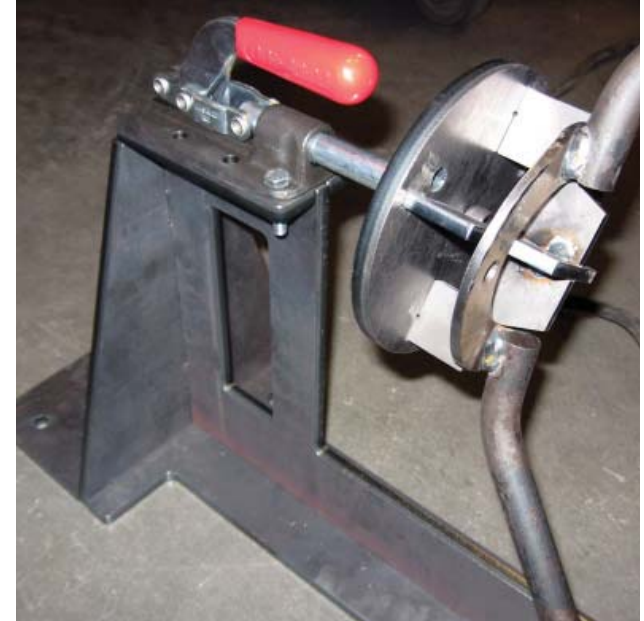
In mass production, the fixture is an external device used to assemble uniform parts into uniform assemblies.



Bench assembly fixture, shown with four flats located



Fixture that serves to locate a ring concentrically with a linear actuator



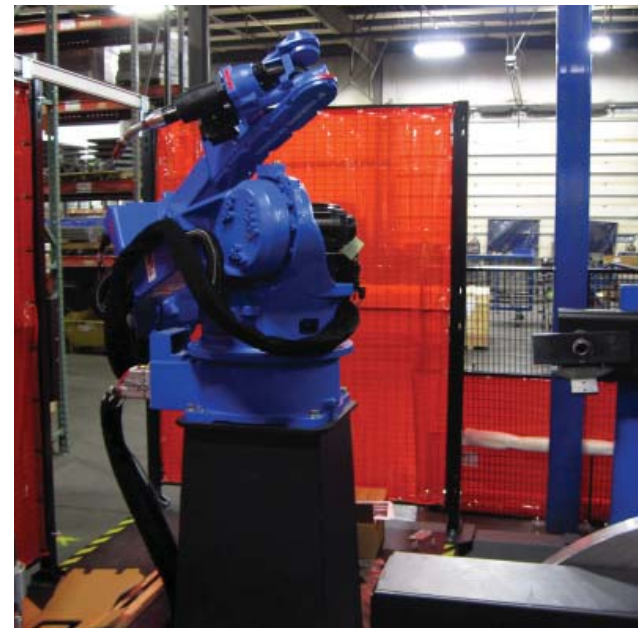
Engaged actuator is locating ring concentrically, and holding the part against a hard stop (not shown)

Manufacturing Processes

TMCO uses a digital fabrication based manufacturing strategy. Welding fixtures are designed and laser cut from steel, then joined via welding. Production parts are laser cut or CNC punched, bent if necessary, then loaded into fixtures. Once located within the fixture, joining occurs via manual or robotic welding. All of this occurs in house.



Laser cutter



Robotic welding arm



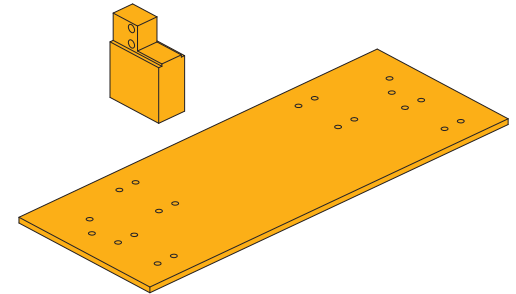
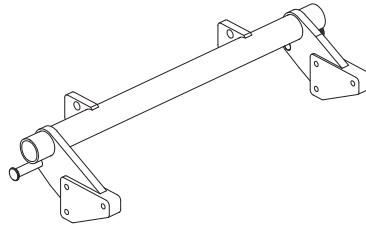
Fixture parts



Assembled welding fixture

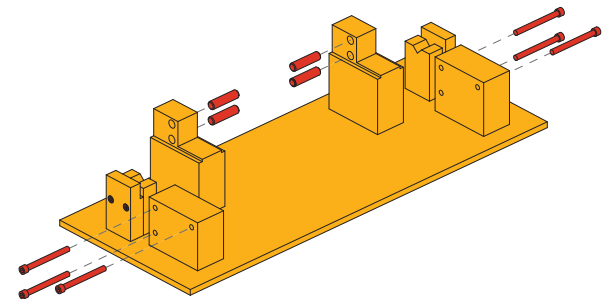
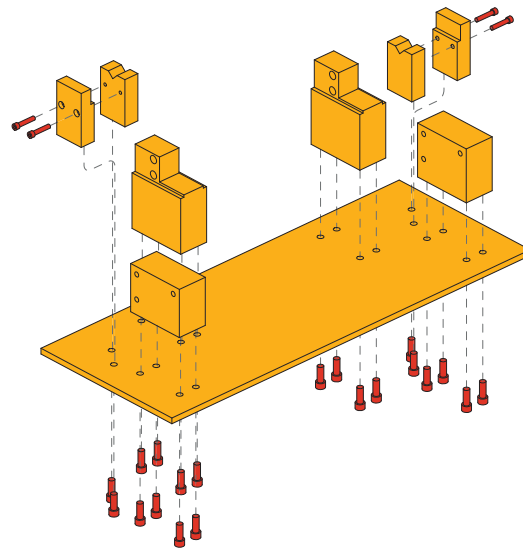
Manual Welding Fixture

This welding/assembly fixture is itself assembled from machined and laser cut parts, ensuring high accuracy. The cost of the fixture is justified by the high number of output assemblies it will facilitate.



Output assembly (the finished unit the fixture is designed to produce)

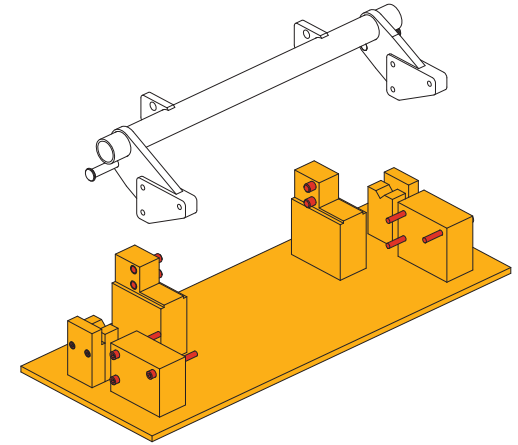
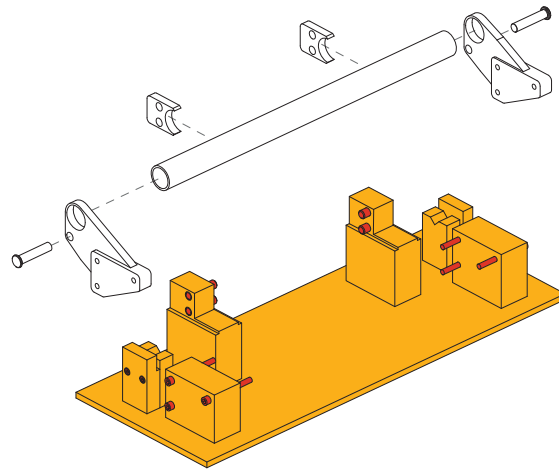
Parts of the fixture (laser cut plate and machined block)



Fixture, assembled with mechanical fasteners, utilizing pre-drilled and tapped holes

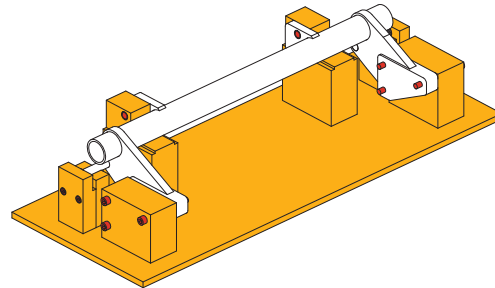
Additional fasteners used to locate the output parts

Manual Welding Fixture

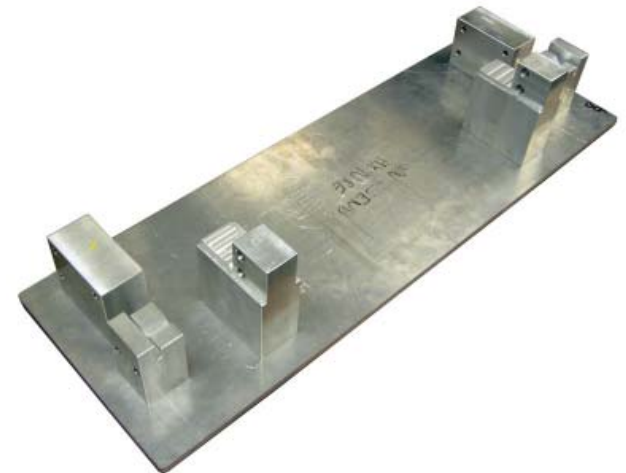


Output parts

Assembly of output parts



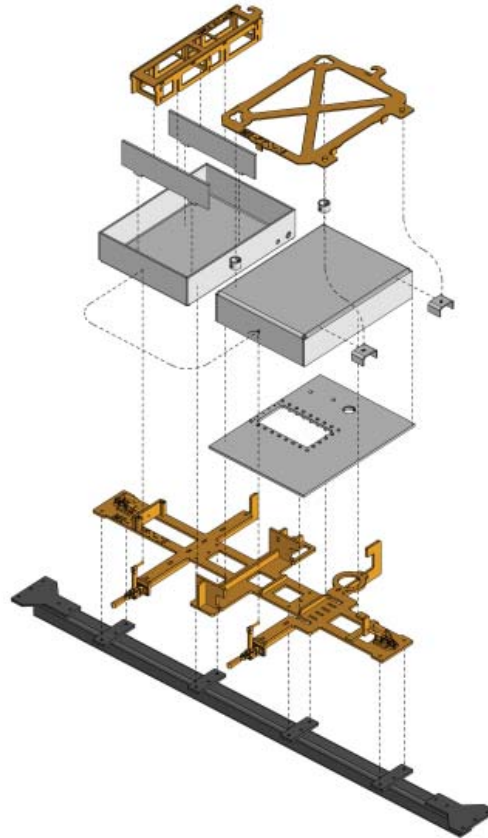
Assembly of output parts, held and located within the welding fixture



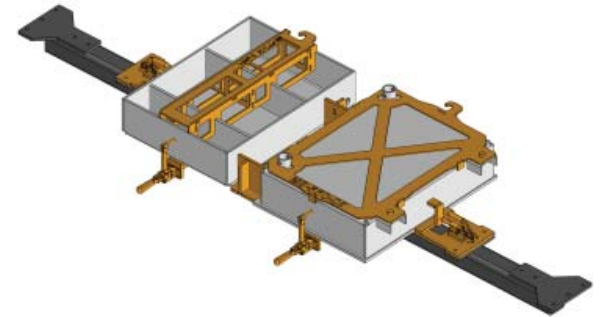
Fixture

Robot Welding Fixture

This is a two-step fixture, so upon the completion of the first weld step (joining the grey baffles to the oil pan, left-hand side) the pan is overturned and a top plat sub assembly is welded to the pan on the right hand side. An operator loads the parts and second step, then triggers a pre-programmed welding pattern.



Exploded diagram



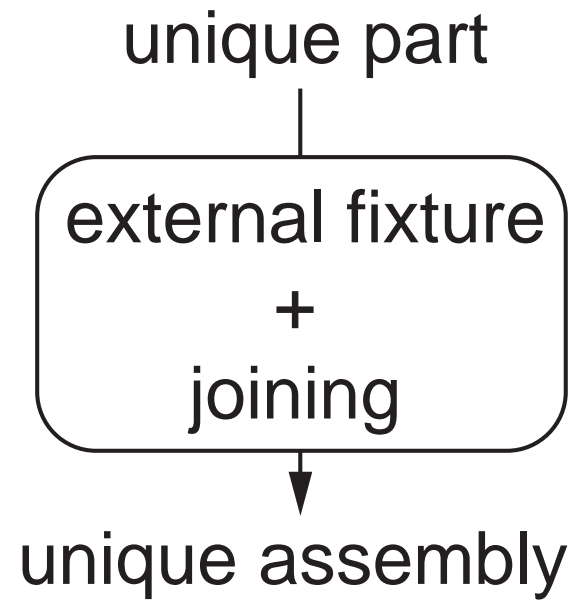
Parts assembled in fixture



Fixture

Architectural Fixture Analogs

Within architecture, there is less of a tendency for mass production, and therefore less conventional use of the fixture. However, fixturing is utilized in a modular manner, notably as formwork. In the case of formwork, the form is the external fixture, and the parts are concrete, rebar, and/or masonry elements.



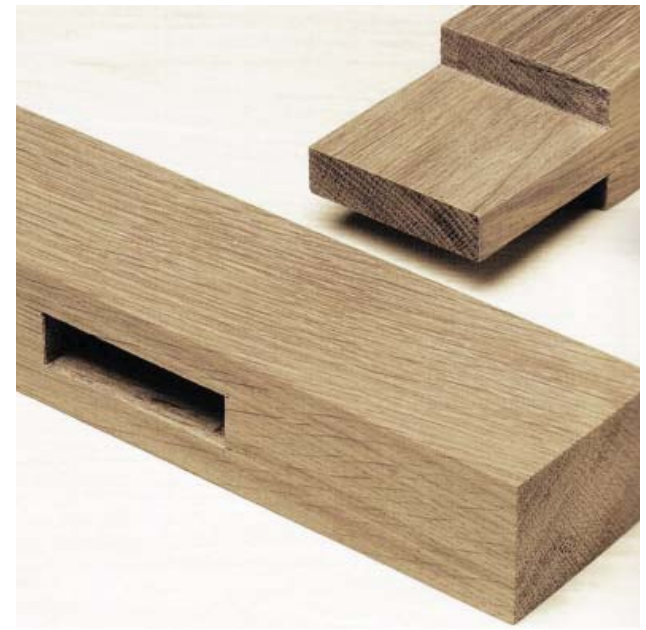
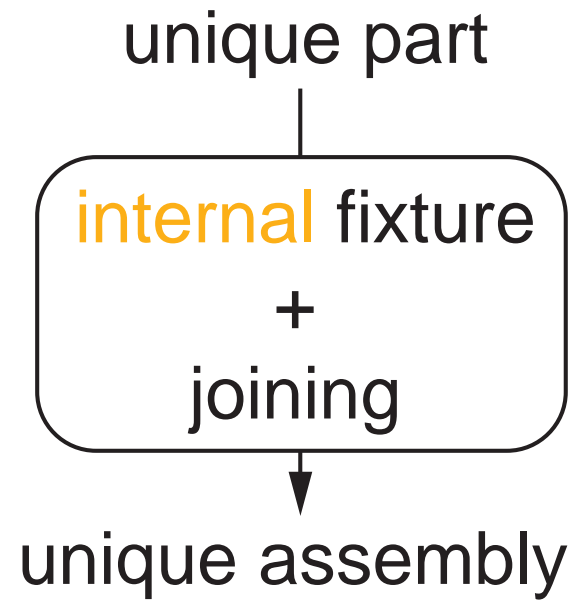
Modular cast-in-place concrete formwork



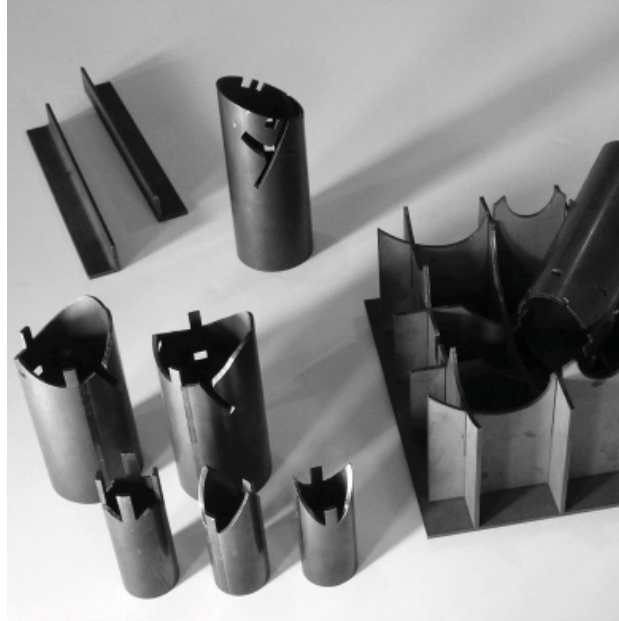
Arch form

Self-fixturing Architecture

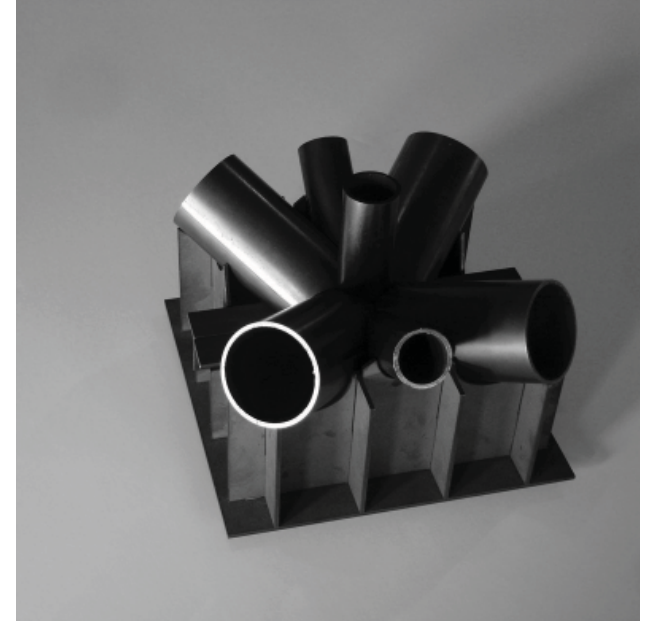
Given the relatively low volume and high specificity of architecture production, joining is typically not facilitated by external fixtures. However, the opportunity exists for fixturing to be imbedded within the part. An “internal” fixture can be economical and expedient to produce in the digital fabrication environment. Internalizing the fixture shifts the labor intensive nature of accurate construction from the hands of the builder into the realm of the designer. Parts must still be manually assembled, but the internal fixture removes the potential for unintended inaccuracy, incorrect installation, and miscommunication - design intent moves directly from CAD to CAM (computer aided manufacturing).



Mortise and tenon assembly, a labor intensive internal fixture



Multi-axis laser cut tubing, a low labor internally fixtured assembly



Assembly of multi-axis assembly

Material

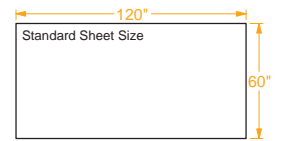
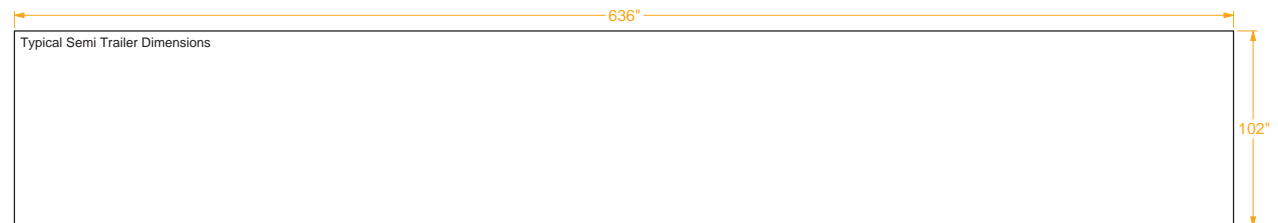
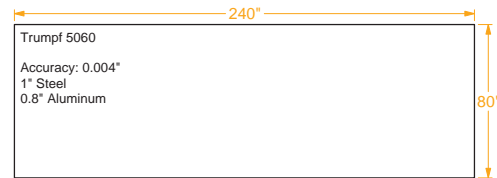
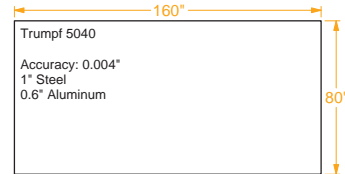
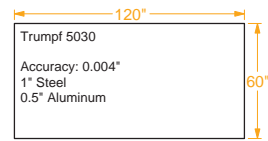
Accepting the process of digital fabrication as the means of production, it is important to consider the specific type of digital fabrication and applicable materials involved. 2.5-axis laser cutting of steel is a logical choice for a number of reasons:

1. 2.5-axis machining is among the most accessible means of digital fabrication, and therefore is applicable to a larger number of people than more exotic processes, such as 6-axis milling. Additionally, 2-axis machining allows physical prototyping to be a large component of the thesis.

2. Wood and other relatively soft materials have been explored excessively in architectural discourse. Steel is a more novel material while retaining a large degree of accessibility (versus, for example, titanium). While 2.5-axis CNC routing can be used for wood, 2.5-axis CNC laser cutting must be used for steel on a large scale (or plasma/water jet cutting).

3. The sheet format of steel is ubiquitous and allows the option of flat pack shipping from the manufacturer to point of assembly, if desired.

4. 2.5-axis machining + a variety of steel stock dimensions means that many scales can be explored and the use of built-up assemblies are facilitated, increasing economy. To provide a counter example, 6-axis machining of an aluminum block into an open-web joist would be more expensive, time consuming, and limited in scale.



Typical laser cutter dimensions have been catalogued in an effort to understand the scalar possibilities of building architectural elements from sheet steel.

Type & Parameters

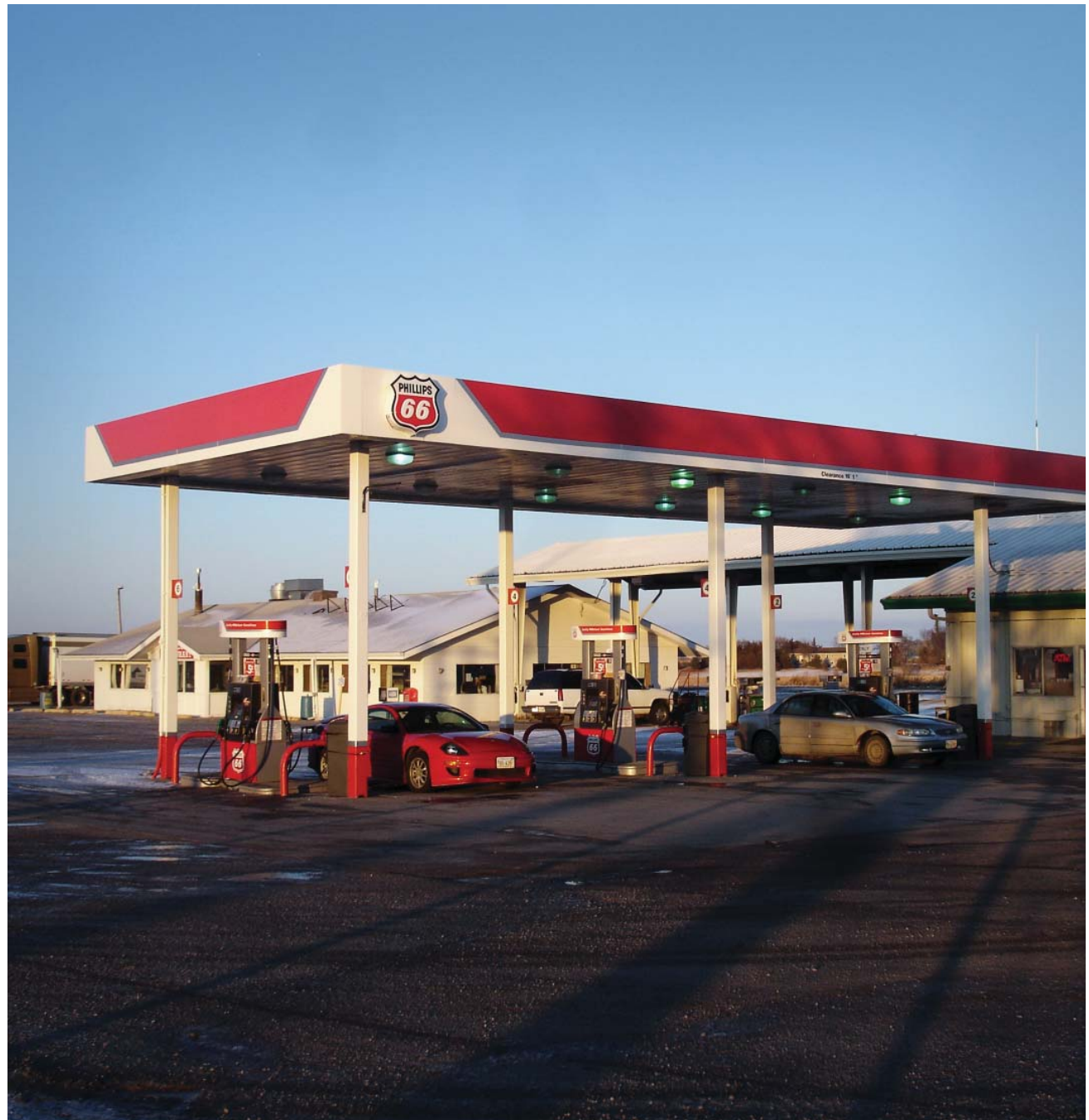
It is useful to select a typology (gas station) such that the design exploration gains a degree of specificity, as opposed to operating in a void.

1. The gas station is a semi-mass-produced entity, lending itself to “specified mass production,” that is, the same genotype is often applied to many sites with minor changes. It is a ubiquitous and “low” building type, like fast food restaurants, that demands economy, yet could benefit from a higher degree of design consideration.

2. This category of ubiquitous architecture is a good analog to manufactured mass production, yet tends to avoid aesthetic associations with manufacturing. Self-fixturing offers the potential to embed the “manu-tech” aesthetic within the gas station. The performative qualities of the gas station can be accentuated, and the concept of fixturing can be imbedded not only within structure and form, but also within systems and even the way in which the gas station is used by its occupants.

3. Moderate structural span lengths permit the use of conventional laser cutting bed and sheet steel dimensions

4. The canopy is a good avenue for exploration. It lacks some confining constraints, such as thermal and environmental enclosure. At the same time, it is more pragmatically architectural than a pavilion, which is often the focus of digital fabrication explorations.



Typical gas station

Repsol Stations

Gas station precedents are gathered as a part of constructing the framework for self-fixturing architecture. The precedents selected exhibit innovative architectural qualities, both tectonically or organizationally.

Spain (200+ sites)
Foster+Partners

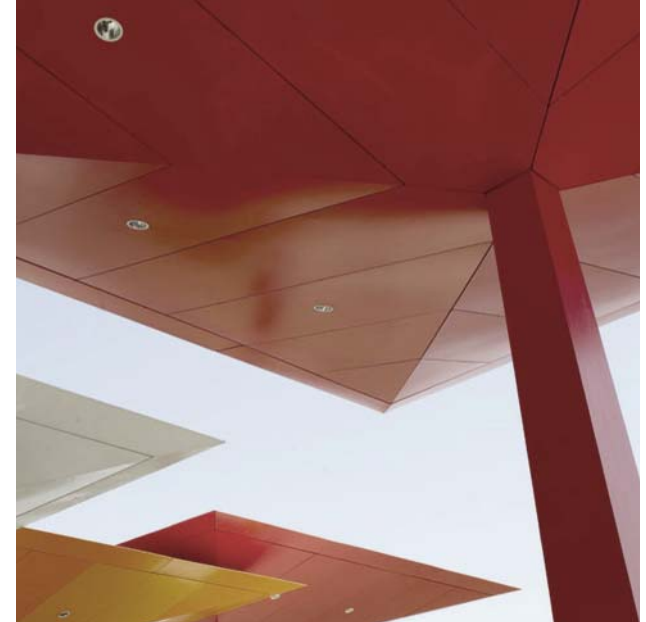
Created as a kit-of-parts, these modular canopies are installed in variable configurations with each other. Essentially autonomous, the canopies offer the benefit of flexibility while arguably making no significant connection to the site nor convenience store.



Repsol station canopies



Repsol station



Repsol station canopy detail

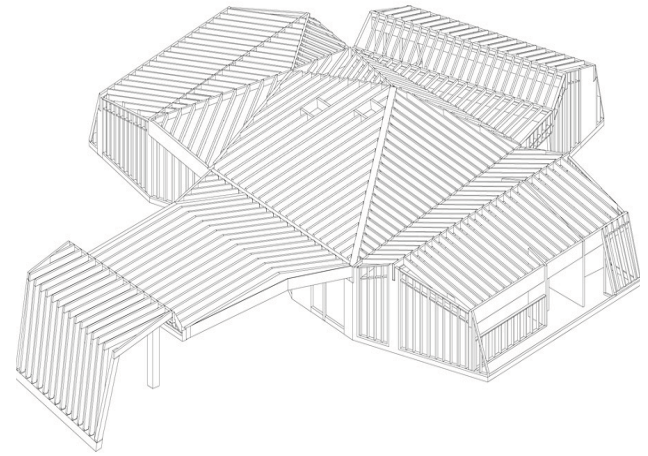
Viamala Raststätte Service Station

Grisons, Switzerland
Iseppi / Kurath

This project is notable for its deviations from typical service stations. Program is revolved around the core and accessible from all sides, unified by a canopy that melds with the service components. A warm wooden interior and structure is clad with steel paneling. Walls and laminated timber frames were prefabricated.



Viamala Raststätte service station



Structural diagram

- 1 Fuel Station
- 2 Entrance Hall
- 3 Bar
- 4 Restaurant
- 5 Shop
- 6 Shop Regional Products
- 7 Garden Restaurant
- 8 Playground
- 9 Toilets
- 10 Conference-Room
- 11 Kitchen



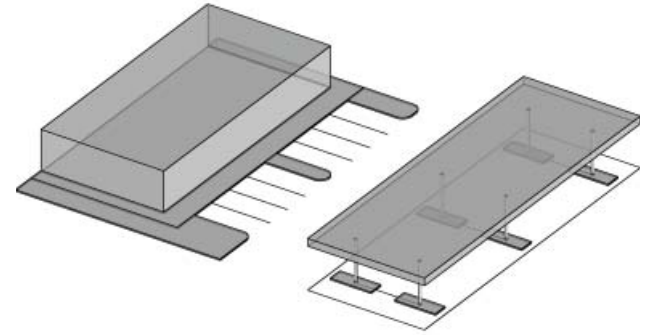
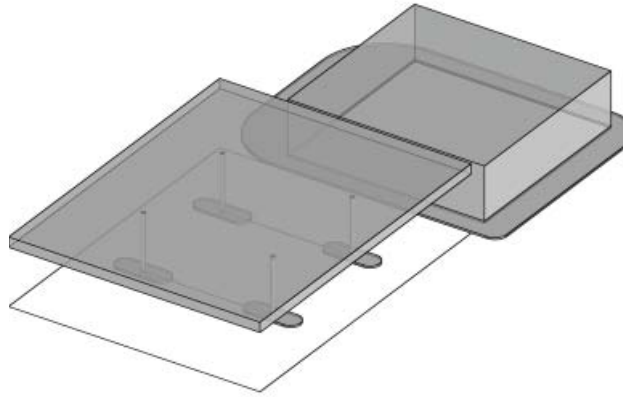
Plan



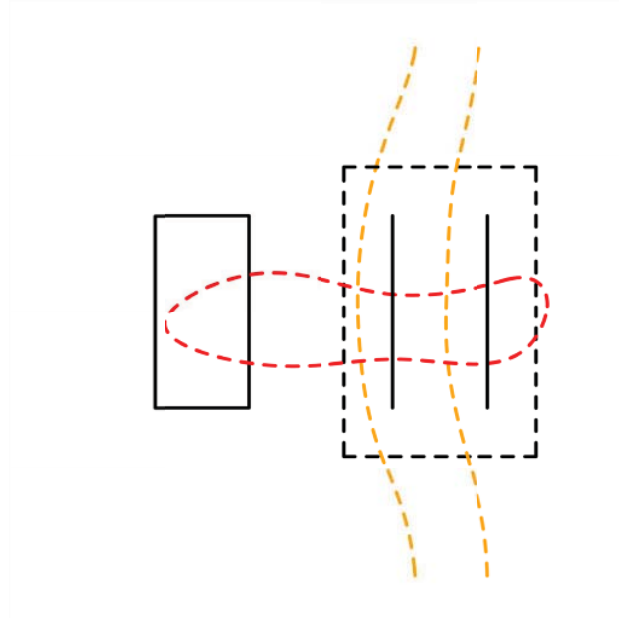
Interior

Gas Station Organization

The typical station is design is highly atectonic. Organization follows a typical logic where the canopy and convenience store have an autonomous or null relationship, in contrast to the precedents. It is important to note that the relationship has changed since the inception of the gas station - the canopy has moved further away from the store.

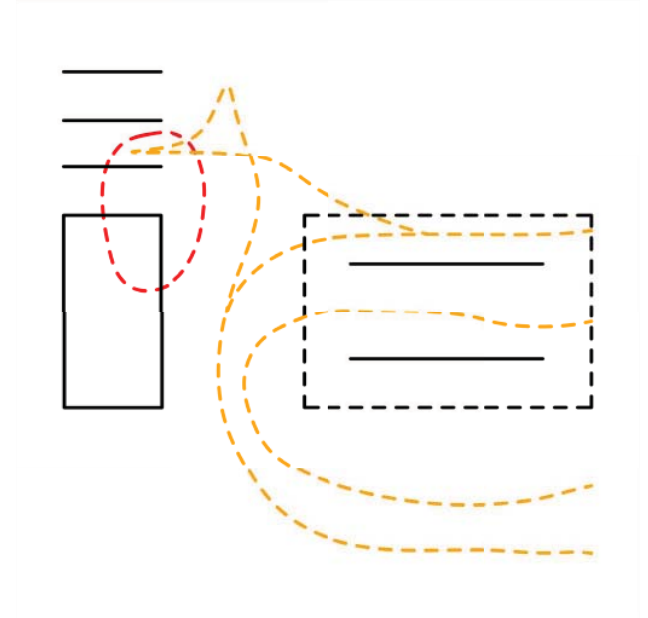


Fuel station massing (4 islands/8 pumps)
Prior to pay kiosk



Diagram, prior to kiosk

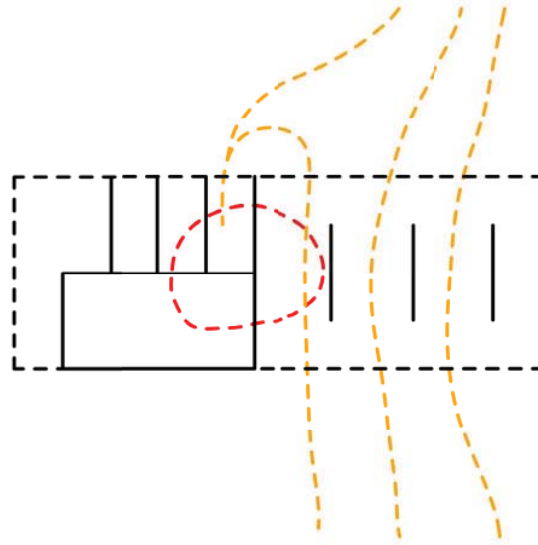
Fuel station massing (6 islands/12 pumps)
After pay kiosk



Diagram, after kiosk

Site

Potential sites are selected in Lincoln, Nebraska. Given the general similarity among fuel stations, as well as the focus of the thesis on tectonic exploration, choosing a specific site is arguably not a critical issue. The sites listed below are made after a conversation with the owner of the U-Stop chain. Criteria include a mostly vacant or deteriorating lot and proximity to high-traffic streets. 19th & "O" is the most favorable site given its proximity to an existing busy street ("O") and a street with plans for expansion (19th). Additionally, the redevelopment in the area suggests increased commercial activity, and the site is currently occupied by a diminutive phone store.



Preliminary organization diagram



Proposed station footprint

19th & "O"
84th & HW6
17th & "Q"
56th & Old Cheney



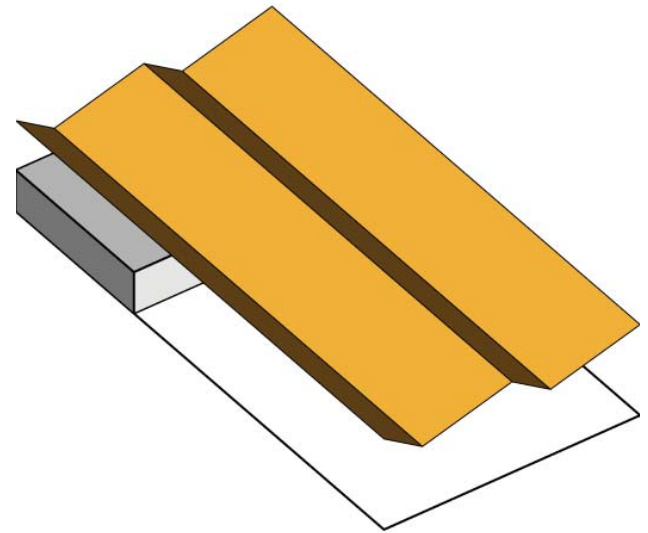
19th and "O"

Canopy Constraints

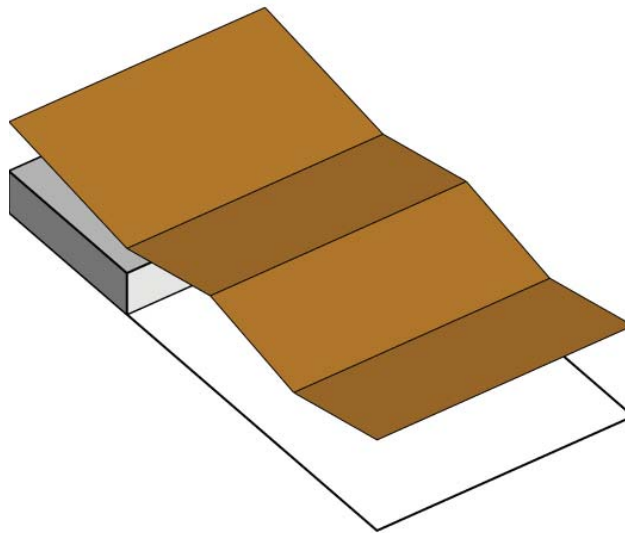
Constraints can inform the design of the canopy and serve as a means of specifying a genotype.



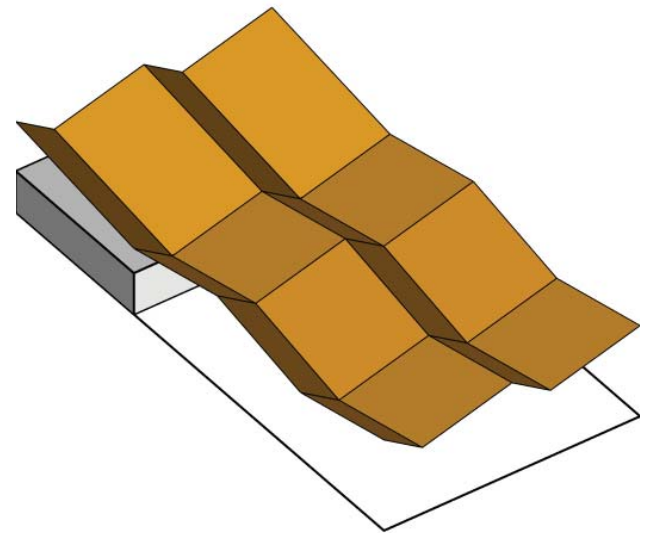
Canopy generators - solar angle/exposure area + drainage to columns



Solar + drainage angle



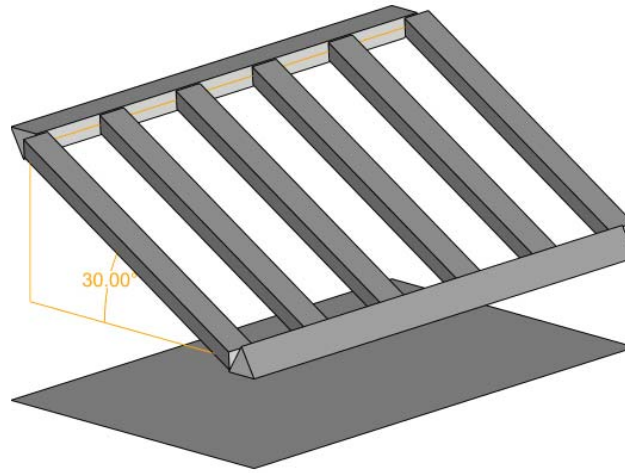
Drainage angle



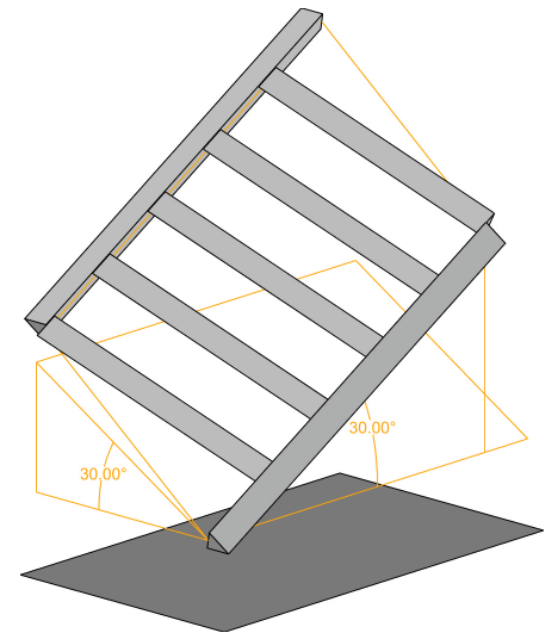
Composite

Genotype Tectonics

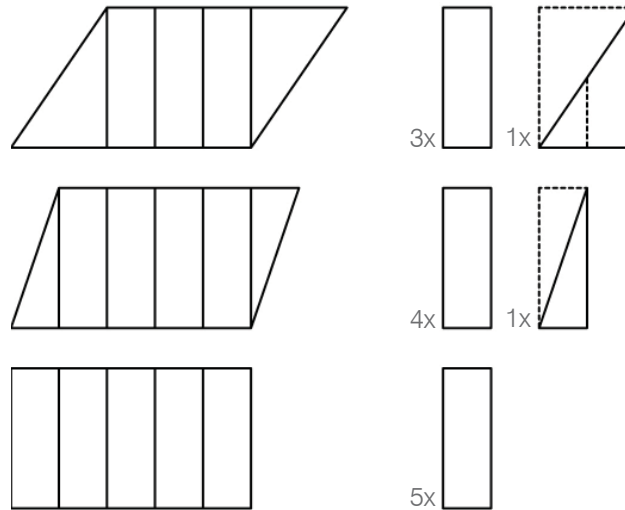
In order to maintain perpendicular connections (a desirable condition when creating connections using 2-axis cutting), panelization must adapt based upon slope. With a single slope, such as rotation to obtain solar angle, a standard rectangular panel may be used. With a double slope, including solar rotation on one axis and drainage rotation on the other axis, the transverse structure can shift to maintain a certain number of standard panels. Non-standard panels can be fabricated in pairs.



Single slope



Double slope

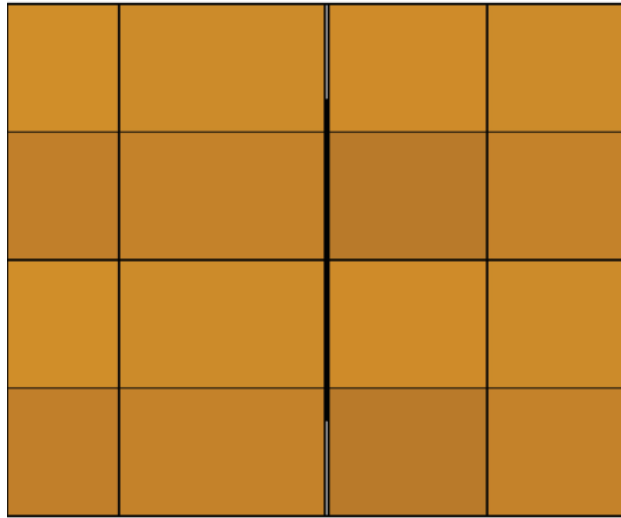


Panel modules

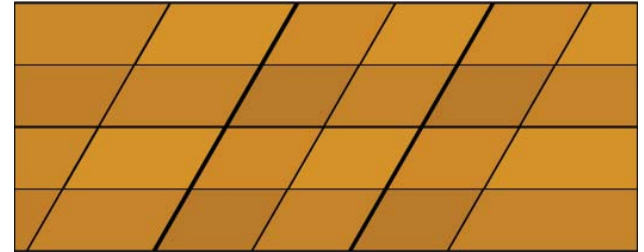
Caption

Parametric Genotype

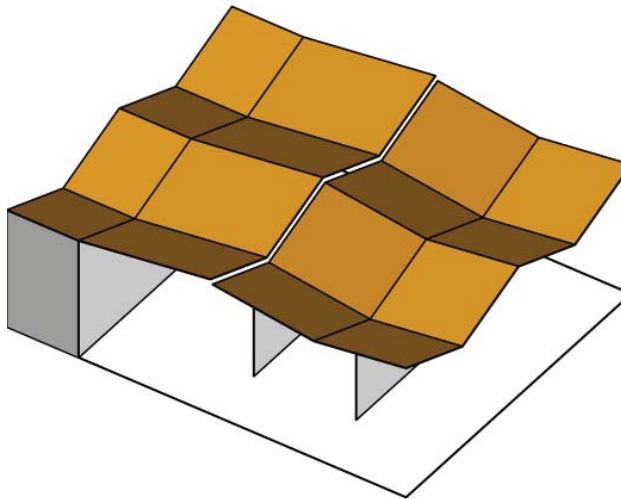
Rough examples of a parametrically driven fuel station are “baked,” responding to variable constraints, such as sun angle, lane angle, canopy height, etcetera. An extensive grasshopper definition creates this genotype based upon the aforementioned constraints as well as a number of additional user-defined parameters.



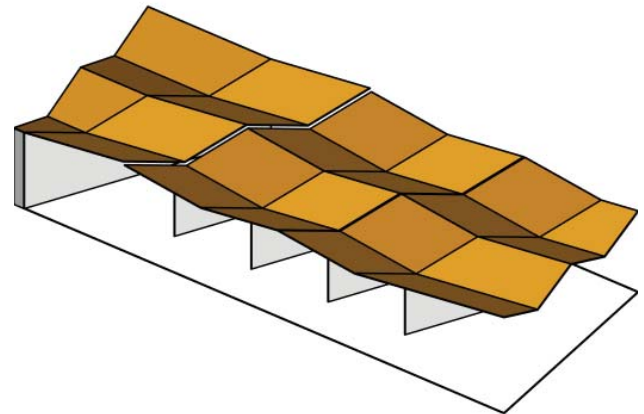
Two 90 degree lanes



Four 60 degree lanes



Two 90 degree lanes



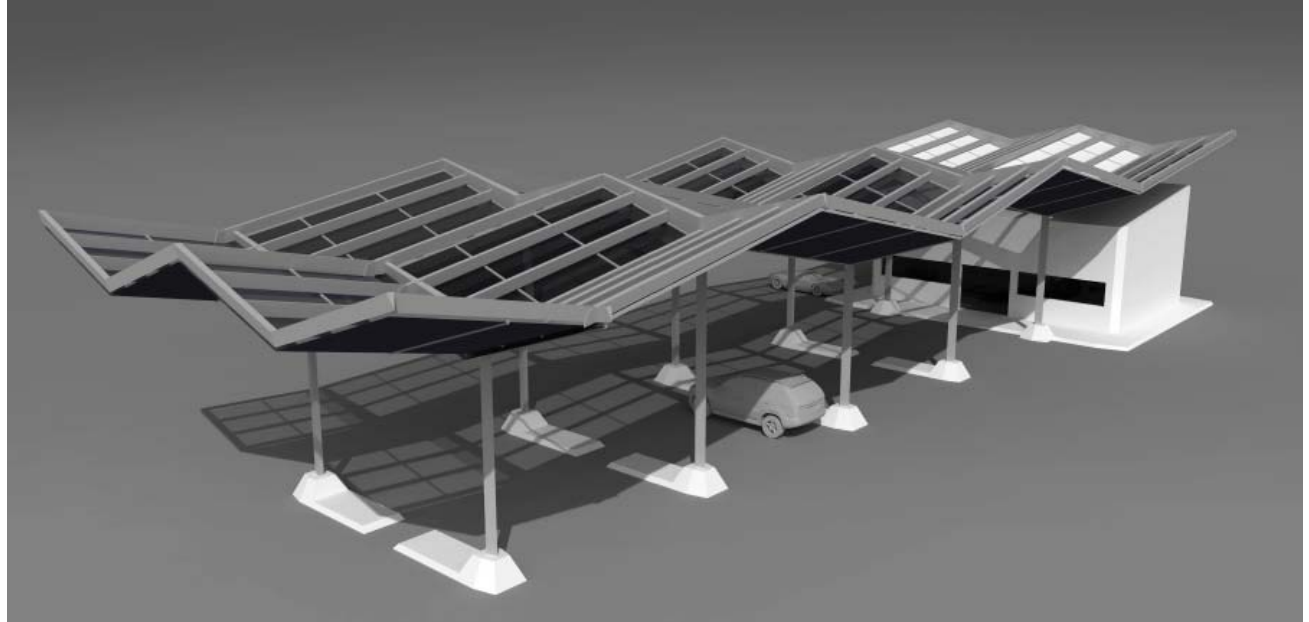
Four 60 degree lanes

Genotype Variation

A schematic-level genotype was baked in two different configurations to demonstrate the parametric control of, in this case, the number of islands that compose the canopy. The canopy is intended to be autonomous from the convenience store, yet related in a contradictory way.



Genotype with two islands

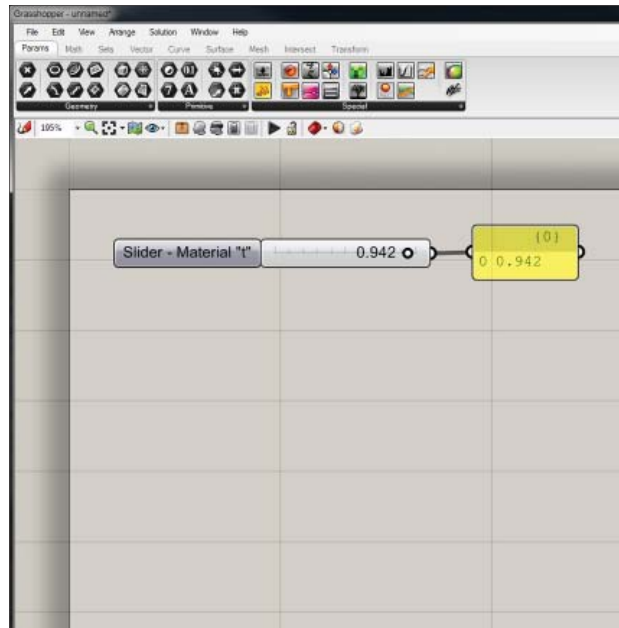


Genotype with four islands

Parametric Workflow

Proposed production methodology

- 1 - Define parameters in grasshopper via genotype, allowing extensive creative control
- 2 - Export parameters to excel (or directly to design table/parameter list)
- 3 - Link to Solidworks/Inventor design table, which controls sketch-based parameters of parts within assemblies. This allows tectonically complex models to be created within specialized software.
- 4 - Export flat patterns from Solidworks/Inventor, manufacture physical parts via CAM



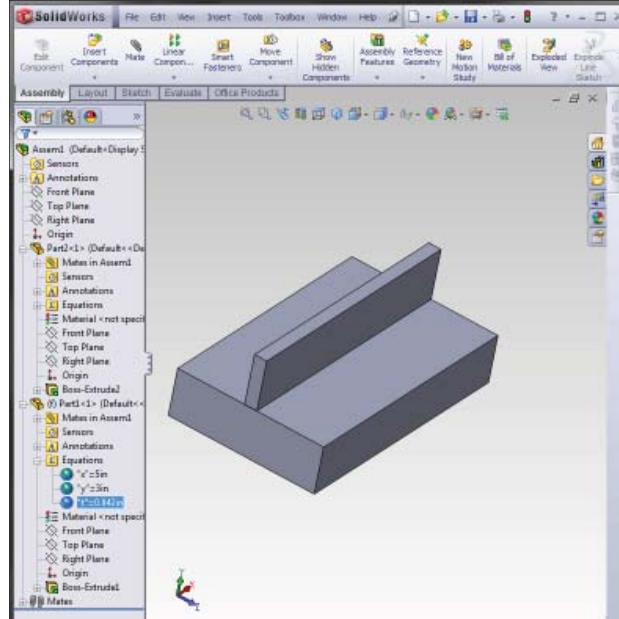
Grasshopper output

The image shows a Microsoft Excel spreadsheet titled 'Part1 - Microsoft Excel'. The spreadsheet contains a design table for 'Part1' with columns A through F and rows 1 through 4. The table is linked to the Grasshopper output.

	A	B	C	D	E	F
1	Design Table for: Part1					
2		x@Sketch1	y@Sketch1	t@Boss-Extrude1		
3	Default	5	3	0.942		
4						

Linked excel table

The images to the right exhibit a proof of concept of the above workflow method, where a basic Solidworks assembly is being controlled by a Grasshopper parameter. Though progress was made towards this parametric linking throughout the thesis, it was not fully executed, as the number of parameters and complexity of establishing relationships between them was more difficult than expected. However, there is arguably promising potential for a parametric genotype to rapidly create a tectonically detailed model, as well as shop drawings and CAM output files, all of which can be parametrically altered at the whim of the designer.



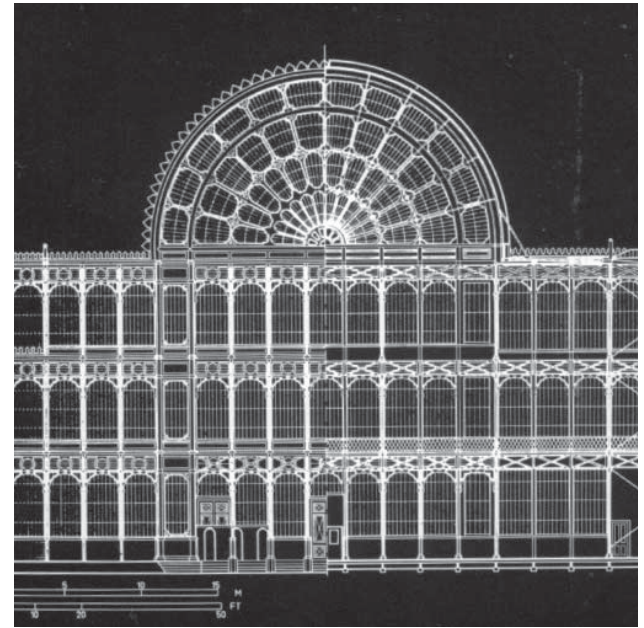
Soliworks assembly

Aesthetic

The self-fixturing canopy is a tectonic exploration of “manu-tech,” a hybrid of high-tech and agri-tech. Manu-tech takes advantage of advanced yet accessible digital fabrication methods while striving to achieve economic production via use of common materials and expedient assembly.



High tech gas station



Crystal Palace



Pragmatic, mass produced architecture

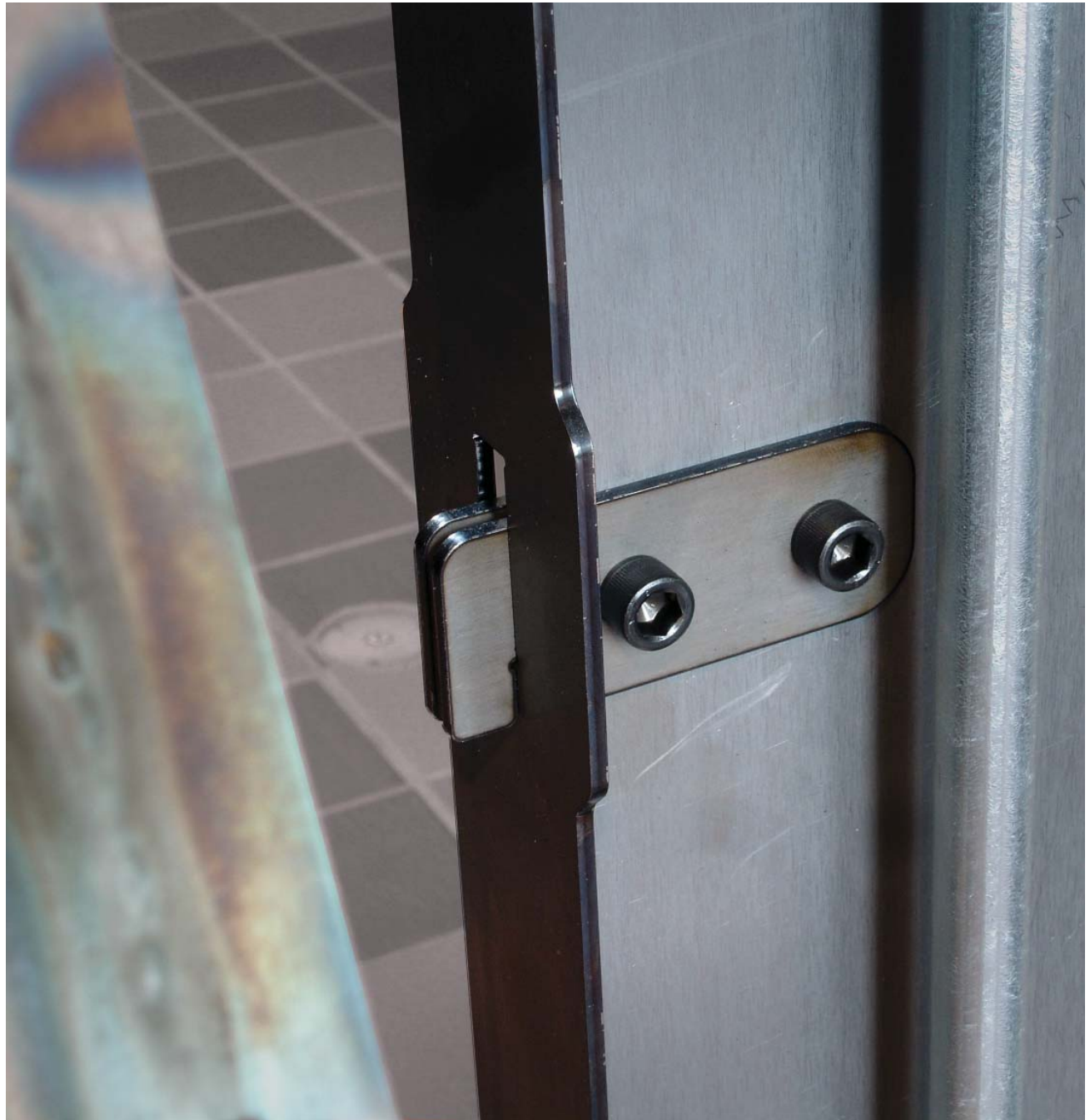


Industry, epitome of manufactured aesthetic

Scale 0

Accurate connection between two or more parts involves several factors - joining method, locating, and holding. Joining can be achieved through adhesive, mechanical fasteners, and welding. In the case of mechanical fasteners (excluding items such as wood screws) accurate holes must be created in both parts to ensure proper assembly.

Connection is facilitated by the internal fixture, which not only locates part relationships within the assembly, but also lends itself to creating a fixed joint.

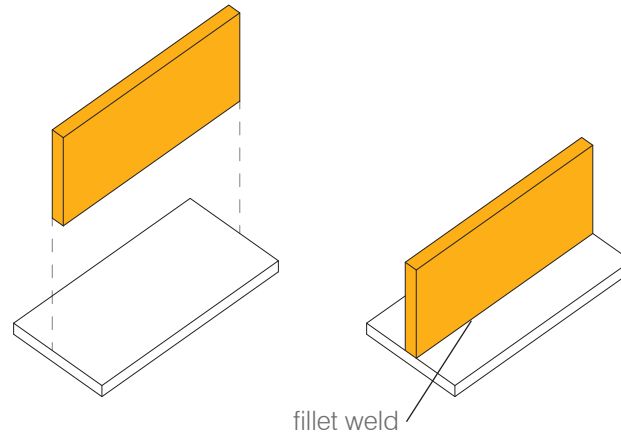


Scale 0 connection within a larger assembly

Scale 0

A catalogue of scale 0 connections has been collected, looking at variations of the butt joint and different joining methods. The butt joint is relevant when considering 2-axis cutting, as all cut edges are perpendicular. As such, the butt joint is the only way to achieve a coincident geometric relationship between a planar face and an edge, and is therefore the most stable means to join material cut with a 2-axis process. However, there are means to create non-perpendicular connections by utilizing multiple perpendicular connections within one joint condition.

This catalogue is by no means comprehensive, but it starts to build and inventory from which larger scales of self-fixturing design can emerge. This is the foundation of the idea of “detail up design.” If, for example, the scale 0 condition is rationalized, then any larger scale that makes use of scale 0 is implicitly feasible, and so on.



Type - reference joint, requires external fixture
Joining - fillet weld

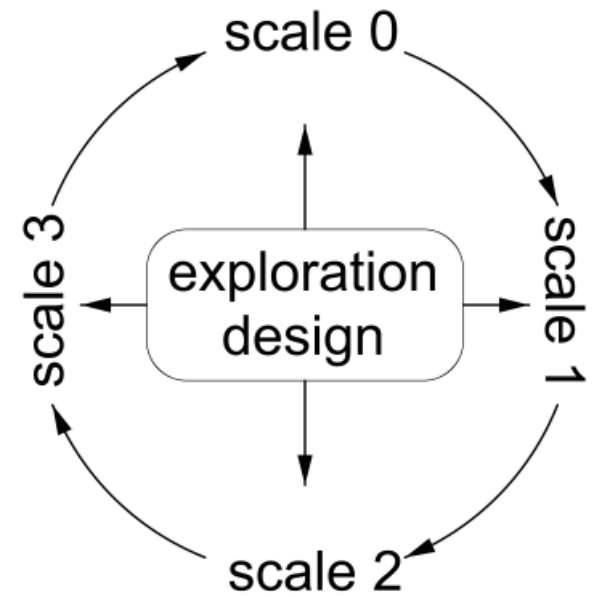
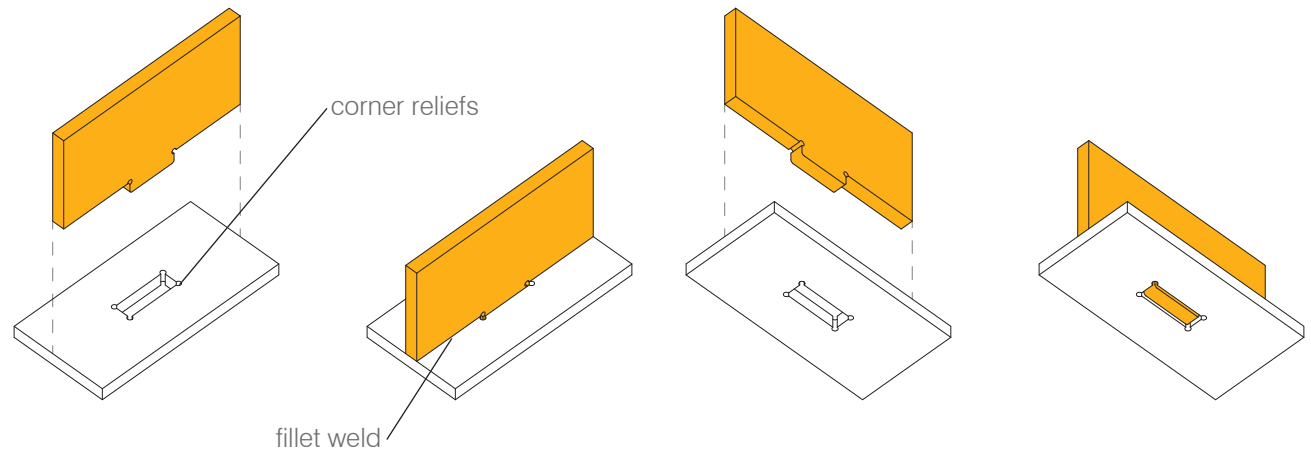
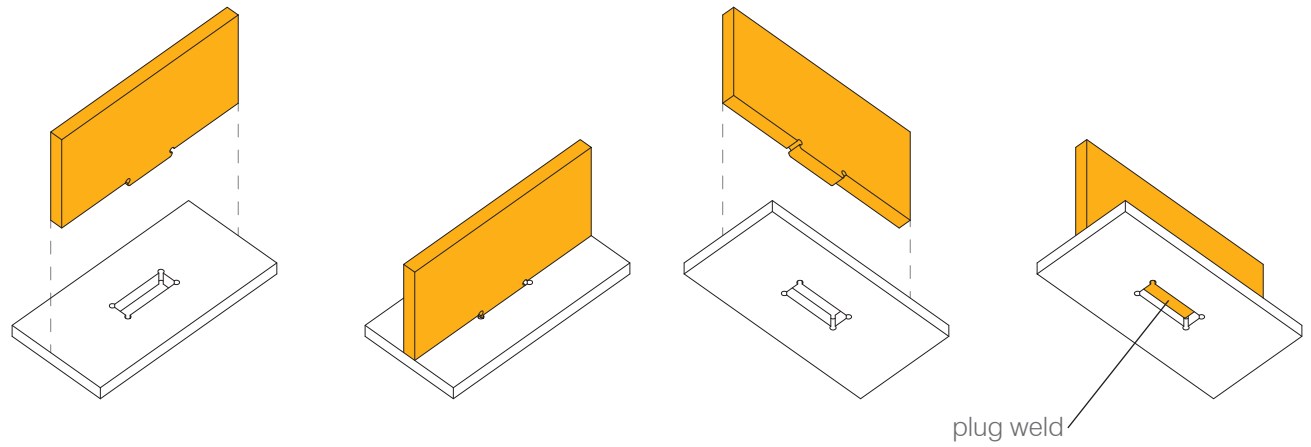


Diagram of scale-based research

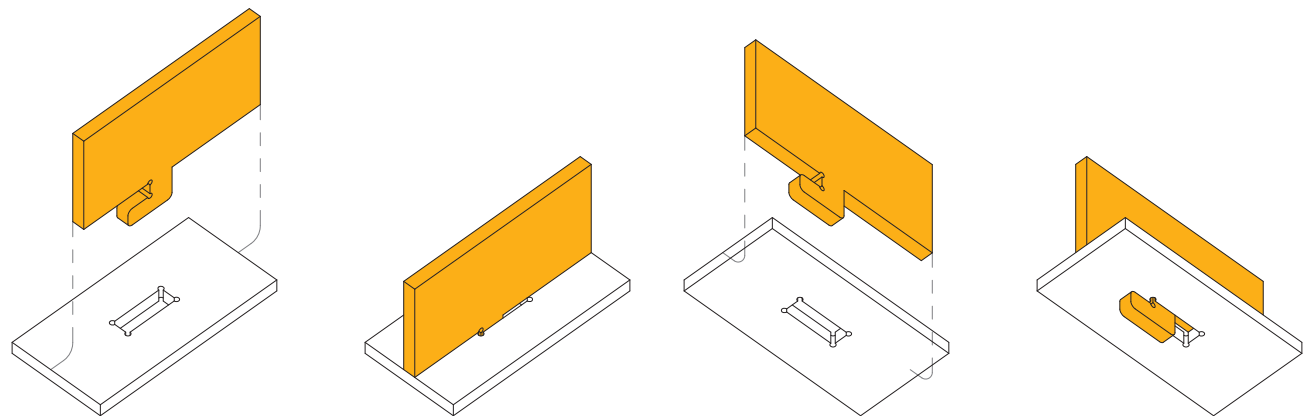


Type - slot and tab butt joint
Joining - fillet weld

Scale 0

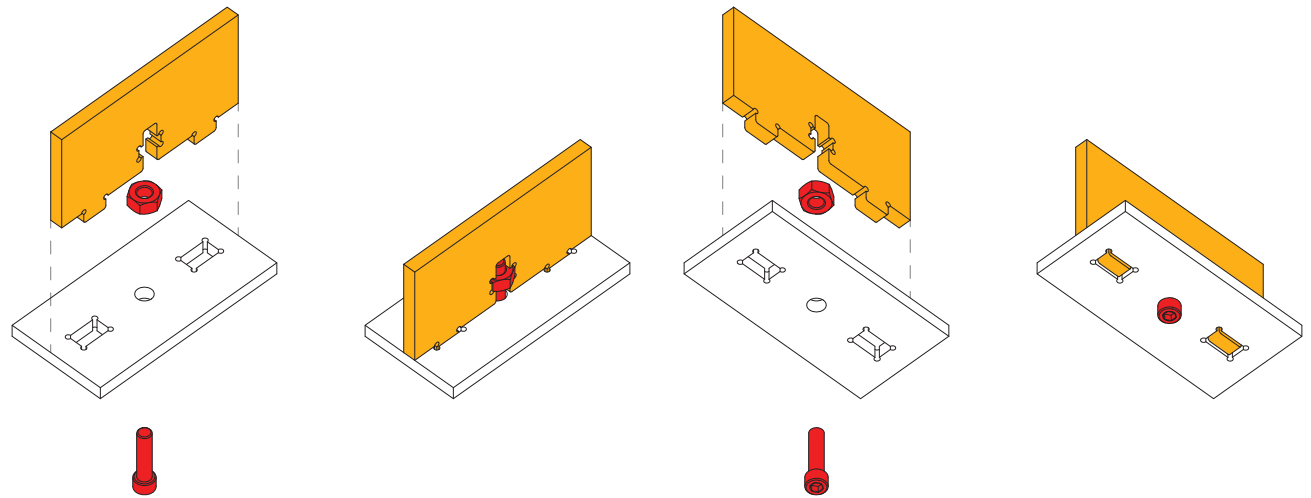


Type - recessed slot and tab butt joint
Joining - plug weld

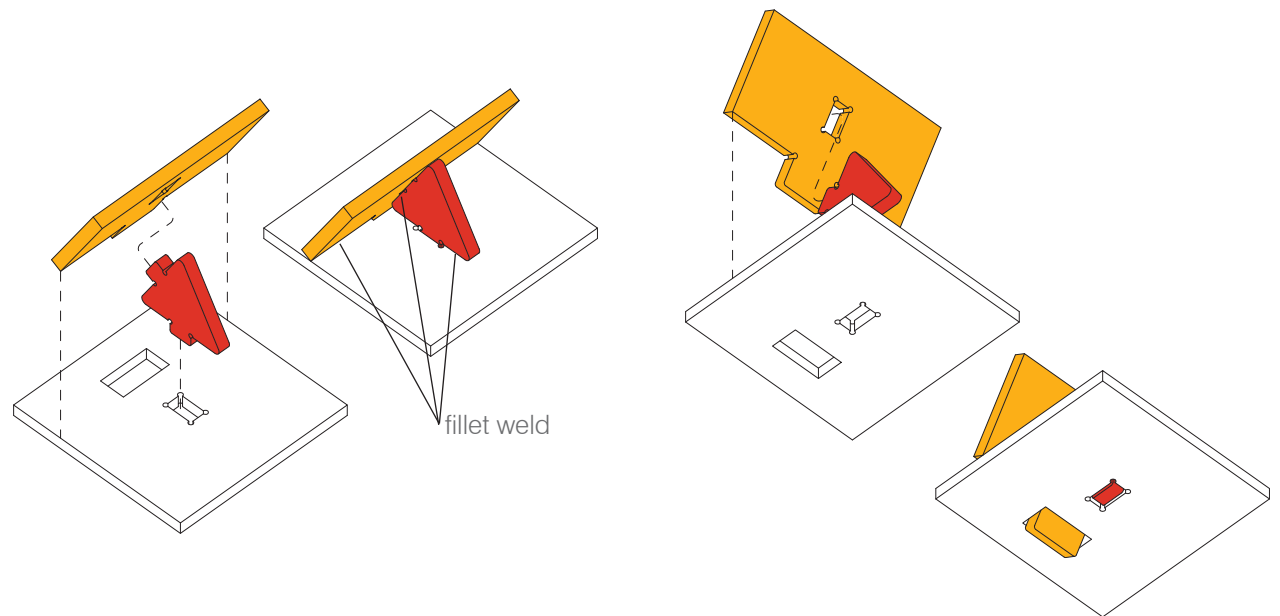


Type - sliding slot and tab butt joint
Joining - gravity assisted

Scale 0



Type - mechanically fastened butt joint
Joining - nut and bolt

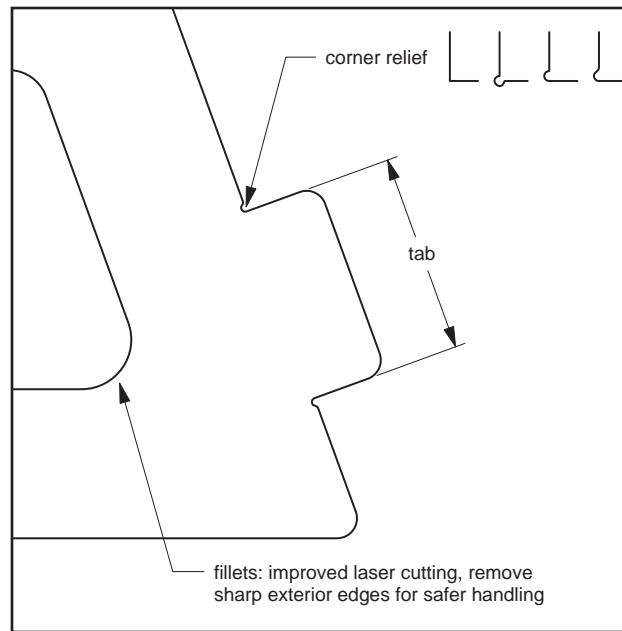


Type - non-perpendicular joint
Joining - fillet weld

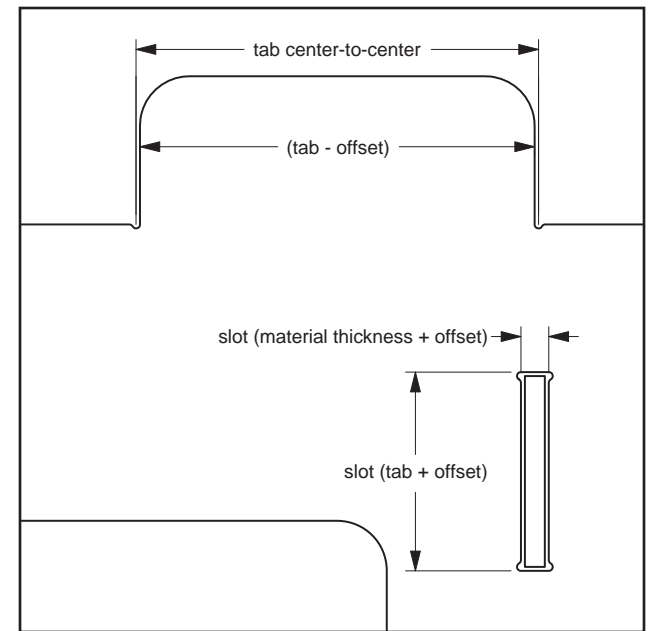
Scale 0

Laser cutting parameters primarily revolve around offsets that accommodate cutting tolerance (typically $\pm 0.005"$). Laser cutters focus a cone of light on a point, which results in a slight taper in the material cut below the point. The taper is increasingly prominent with thicker material, requiring a more generous offset. A fit that is too tight requires manual filing, but a fit that is too loose begins to compromise the accuracy and durability of fixtured connections.

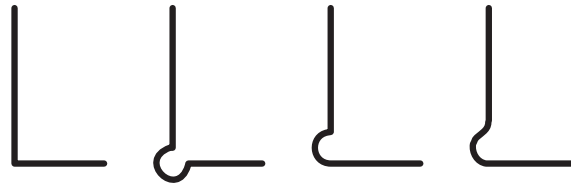
The corner relief is used to relieve stress in bent flanges, or in the context of laser cutting, serves to eliminate the potential for slag to build up in what would otherwise be a right angle cut. A basic solution is to cut a circle centered on the corner. However, the laser cutter, being a high-speed device, possesses high inertia. Therefore, it is logical to assume that the negative effects of inertia are mitigated by subtle changes in direction versus abrupt changes. A curved corner relief in a slot achieves a smooth corner condition while also providing clearance for a tab. Additionally, there is a degree of aesthetic elegance in a cut that is composed of a continuous curve versus purely orthogonal cuts. This is achievable on a large scale only through digital fabrication. Additionally, the parameters involved in this level of detail control demand intelligent linking of parameters so as to automate the design process.



Corner reliefs and fillets



Slot and tab tolerance/offset

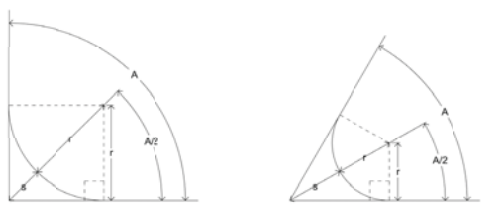


Corner relief evolution

Scale 0

The fillet's main function is to make material handling safe by removing sharp edges. It also reduces inertia and tends to produce cleaner cuts.

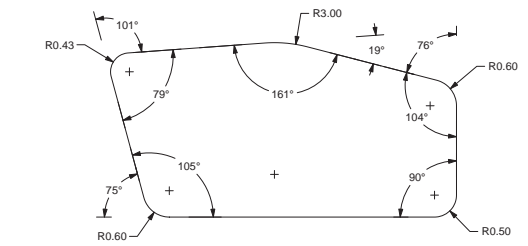
Beyond pragmatic concerns, the aesthetic of the fillet was examined intensely. Applying a 1/4" radius fillet to every corner of a part, for example, will result in a variety of aesthetic conditions unless every angle in the part is the same. An obtuse inside angle will produce a fillet that appears smaller, and an acute inside angle will produce a fillet that appears larger, despite the fact that all possess the same radius. Therefore, several methods were explored to manually alter the radius based upon the angle in question so as to create a more aesthetically continuous series of fillets.



right angle example, with a fillet of r and constant of s

acute angle example

$\sin(A/2) = r / (s + r)$
solve for r, such that given any angle A between two lines and a constant s value, r can be determined.



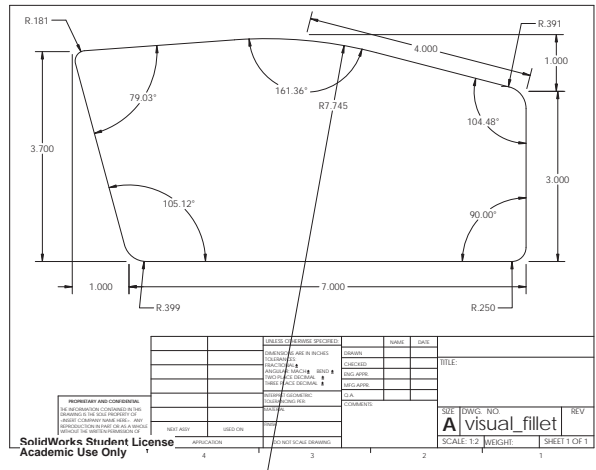
RADIUS	90.00	45.00	15.00	30.00	45.00	60.00	75.00	90.00	105.00
0.25	0.25	0.50	1.50	0.75	0.50	0.38	0.30	0.25	0.21
0.50	0.50	1.00	3.00	1.50	1.00	0.75	0.60	0.50	0.43
0.10	0.10	0.20	0.60	0.30	0.20	0.15	0.12	0.10	0.09

Equation driven fillet logic

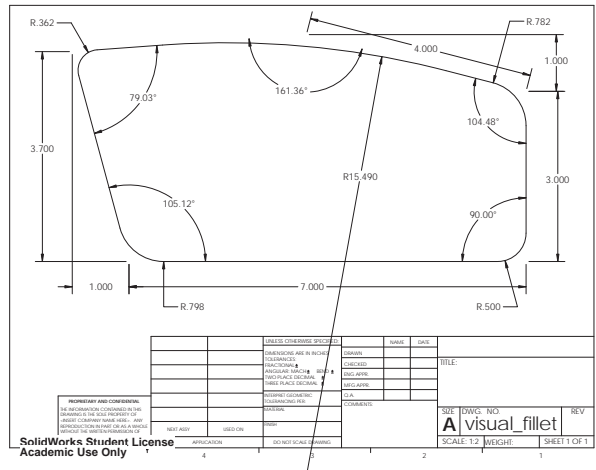
Spreadsheet driven fillet results with a reference radius of 1/2" at the 90 degree corner

The first method is equation driven, and uses the angle of a given corner to determine the radius of the fillet at that corner. This method, while an improvement, produced visually inconsistent results.

A more straight forward method was to simply create a spreadsheet containing fillet radii based upon linear relationships with given angles. As an example, if a 90 degree corner has a fillet with a 1/2" radius, then a 45 degree corner should have a fillet with a 1" radius, and so on. This method is used on many of the filleted corners of laser cut parts seen at larger scales.



Equation driven fillet results with a reference radius of 1/4" at the 90 degree corner



Equation driven fillet results with a reference radius of 1/2" at the 90 degree corner

Scale 1

Scale 1 sub-assemblies utilize different Scale 0 joint types to achieve a variety of assemblies or sub assemblies to be consumed in Scale 2 assemblies. The exploration at this scale focuses on the linear member prototype, manifested as either a structural beam or column. There is an established potential for Scale 1 assemblies as finished products, such as furniture. As part of a competition, the self-fixturing potential of Scale 1 furniture was proposed.



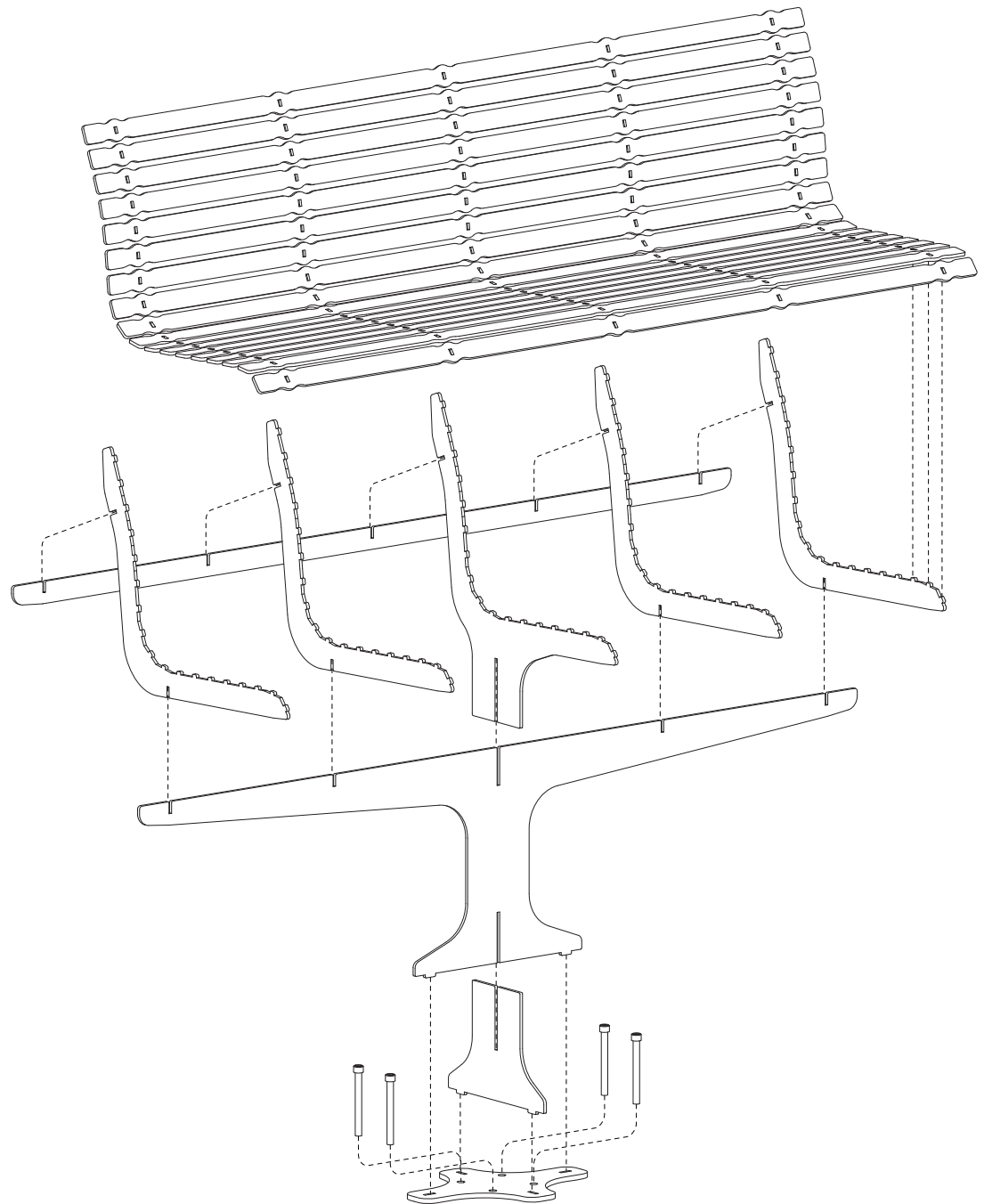
Scale 1 beam/column prototype

Self-fixturing bench

Competition entry:

The Tectonic bench is designed with two primary considerations. First, the bench is self-fixturing. In other words, no external fixture is required to assemble the parts (that is, hold and locate the parts). All parts are laser cut from 1/4" steel (with the exception of the 3/8" stainless steel bolt plate for corrosion resistance). Given the fact that laser cutting is used, little additional effort is required to design slot-and-tabbed connections within each part. The parts can therefore be fitted together with ease. Relatively few welds are required to solidify the assembly. Plug welds can be used to join the straps to the braces, and then ground smooth.

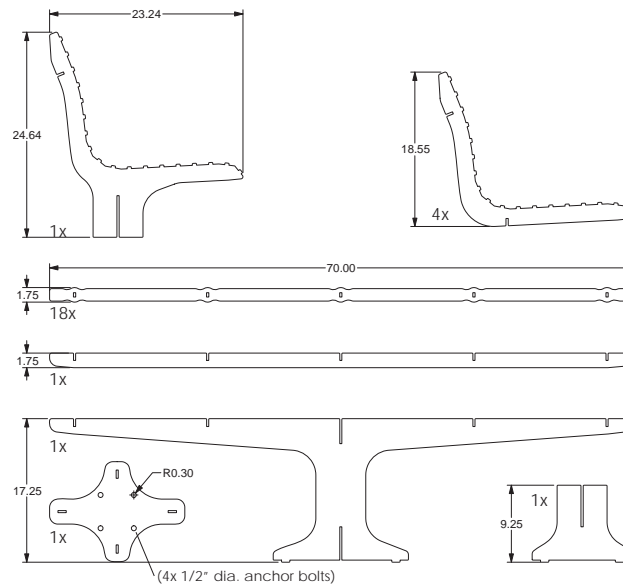
Second, given the fact that an assembled bench does not require the fabrication of an external fixture, it is realistic to offer a large degree of dimensional variability. Parametrically controlled parts can be altered by changing a few key variables, and new flat-patterns can be exported for laser cutting. This gives the customer control over many parameters, such as the length of the bench. The 70" long example could easily be shortened to 64", and the assembly process would be identical. Additionally, a customer could theoretically choose to engrave custom font or graphic motifs in any part of the bench.



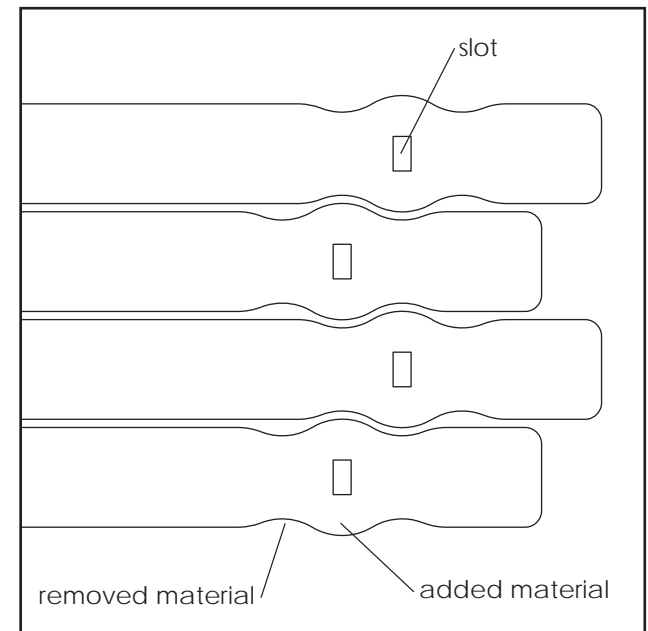
Exploded diagram of bench assembly

Self-fixturing bench

To the immediate left, a detail of the laser cut nesting layout of longitudinal bench straps, showing slot locations. Extra material is added adjacent to the slot to maintain sectional strength, and complementary material removals occur to allow optimal laser cutter nesting, as demonstrated in the staggered pattern which maintains the same density as nesting straight 1-3/4" straps. (1-3/4" stock material could be used to avoid laser cutting, but a large degree of self-fixturing would be sacrificed)



The flat patterns for each part of the bench assembly. The 70" long default configuration is shown.



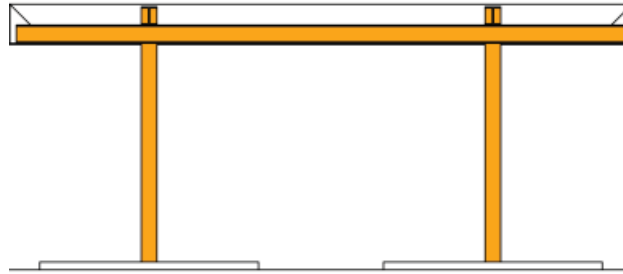
Detail of the laser cut nesting layout



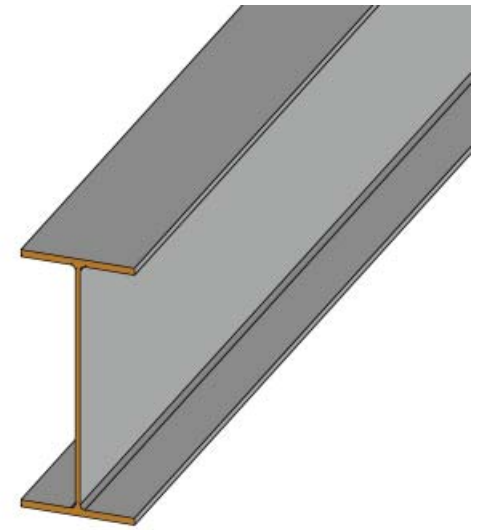
Render, back of bench

Scale 1

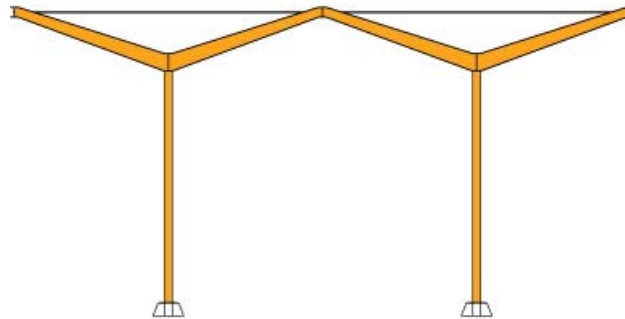
A conventional W-shape is arguably the most efficient given existing steel mill manufacturing capabilities. The W-shape could be replicated utilizing 2-axis laser cutting and self-fixturing parts, and this would offer the advantage of the designer being able to specify all parameters, such as the thickness of each part, as well as any value of depth and width - stock materials would not be a limiting factor. A building could be designed regardless of what standard shapes were available at a steel mill.



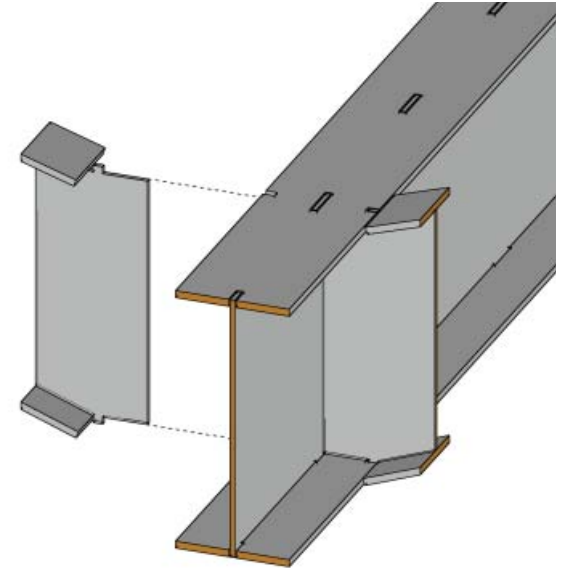
Scale 2 projection of typical W-shape



Scale 1 typical W-shape section



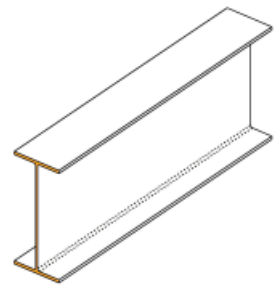
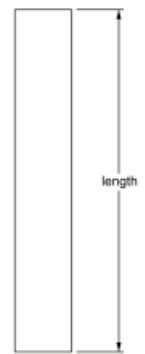
Scale 2 projection of fabricated W-shape



Scale 1 fabricated W-shape section

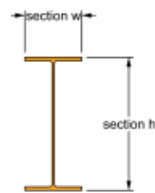
Scale 1

Comparison of parameters between a typical section and fabricated, self-fixturing section. Increased parameters have the advantage of increased flexibility, specificity, and of course implicit fixturing.



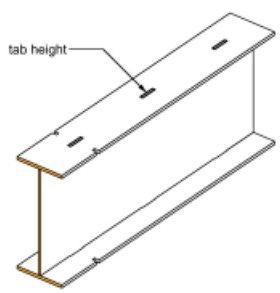
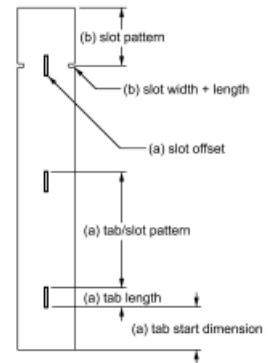
length
section

beam (1x)	
	L
example: W10 x 19	



Typical W-shape parameters

Typical W-shape parameters

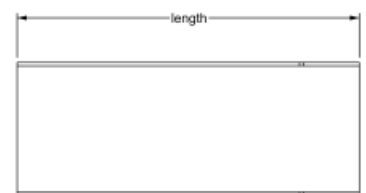
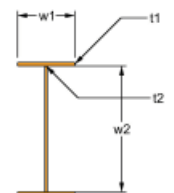


length
width 1
thickness 1
width 2
thickness 2

tab a start dimension
tab a pattern dimension
tab a pattern iteration
tab a length
tab a height
slot a offset

slot b start dimension
slot b pattern dimension
slot b pattern iteration
slot b width
slot b length

flange part (2x)		web part (1x)	
	L		L
	w1		
	t1		
			w2
			t2
	ta1		ta1
	ta2		ta2
	ta3		ta3
	taL		taL
			taH
	sa0		
	sb1		
	sb2		
	sb3		
	sbW		
	sbL		

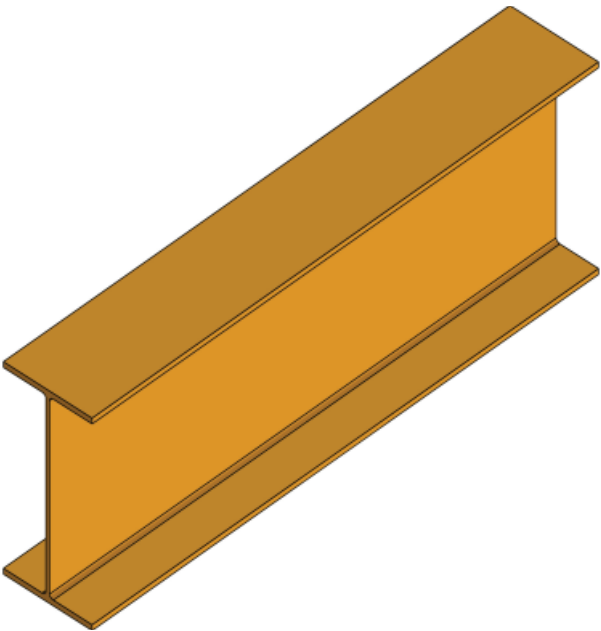


Fabricated W-shape parameters

Fabricated W-shape parameters

Scale 1

Despite the increased complexity of a fabricated section, rough estimating indicates a lower cost. Large mill runs of typical sections would likely result in a lower cost, but it is useful to know that fabricated sections are theoretically economically feasible.



Typical - 3' section

	(lb/ft^3)	(lb/in^3)	volume (in^3)	weight (lb)	(\$/lb)	TOTAL
mean	493.5	0.29	283	80.82	\$1.28	\$103.65

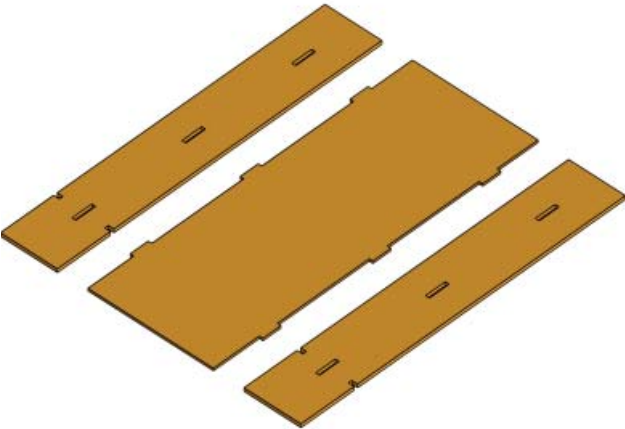
	(lb/ft^3)	(lb/in^3)	volume (in^3)	weight (lb)	(\$/lb)	material cost
mean	493.5	0.29	280	79.97	\$0.50	\$39.98
low	484					
high	503					

	cutting length (in)	(ft)	(\$/ft)	cutting cost
	307	25.58	\$1.00	\$25.58

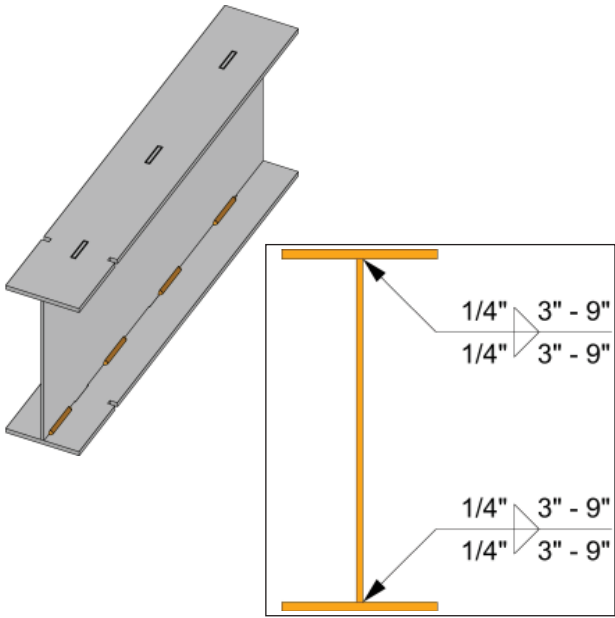
	approx. welding length (in)	(ft)	(\$/ft)	welding cost
	48	4	\$3.25	\$13.00

	TOTAL
	\$78.57

Economics of typical and fabricated sections



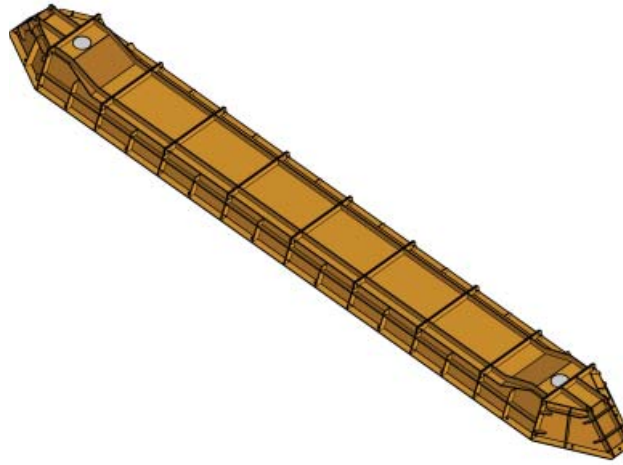
Fabricated - 3' section (flat patterns)



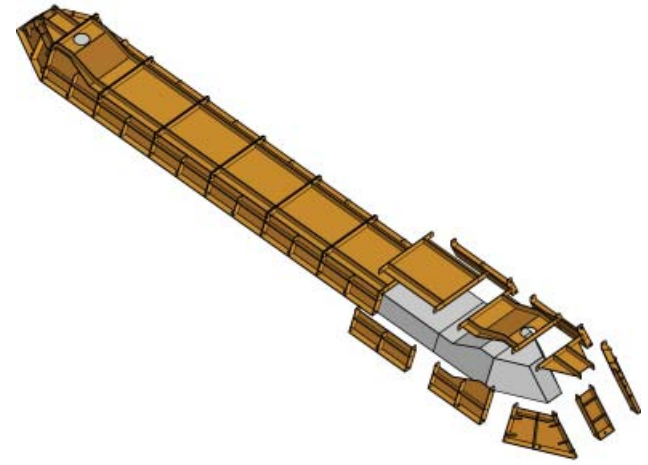
Fabricated - welding solution

Scale 1 Formwork

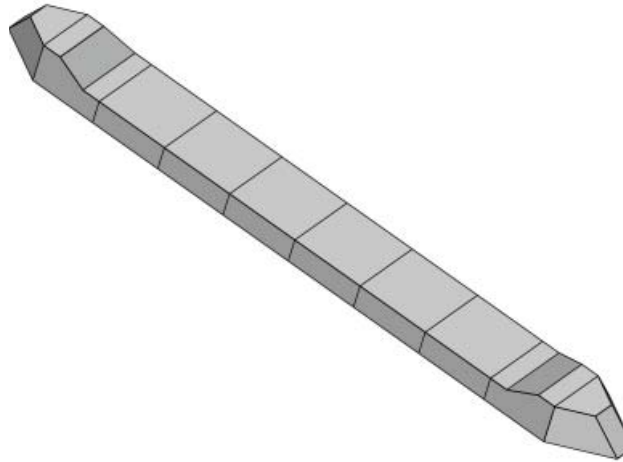
Installation and removal of concrete formwork constitutes approximately half of concrete construction costs. Prefabricated forms offer numerous benefits, but are typically limited to standard shapes. Utilizing digital fabrication and self-fixturing, unique forms can be rapidly produced. While concrete formwork is not the primary agenda of the thesis, it is an interesting avenue through which laser cut steel can be used.



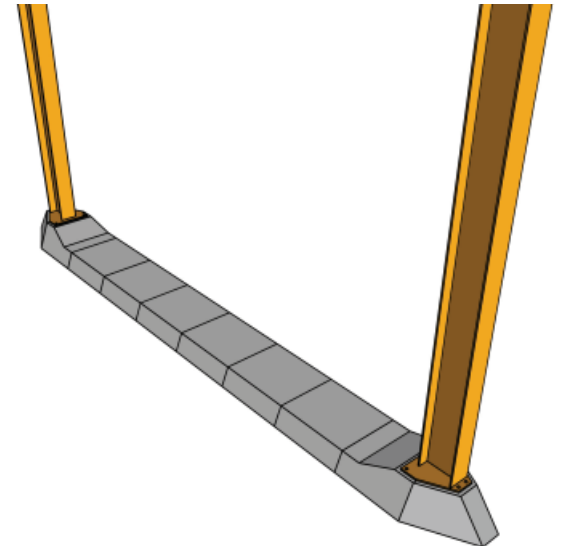
Complete formwork assembly



Exploded sub-assemblies



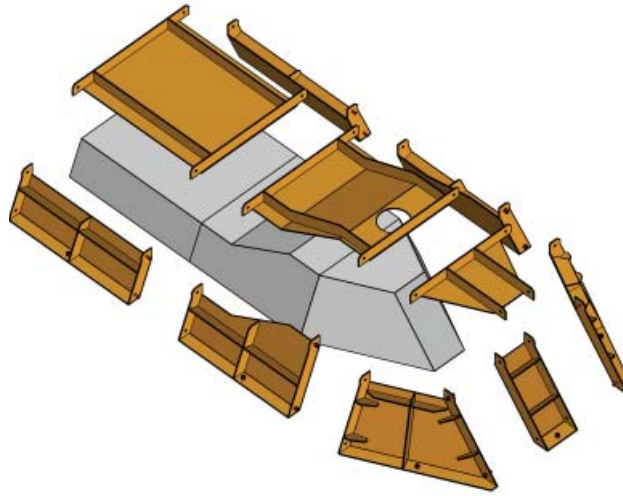
Resultant cast-in-place concrete



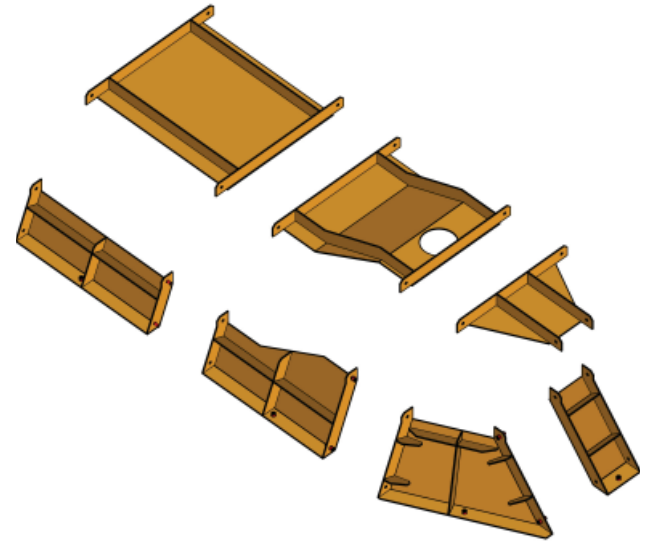
Concrete as part of prototypical fuel station island

Scale 1 Formwork

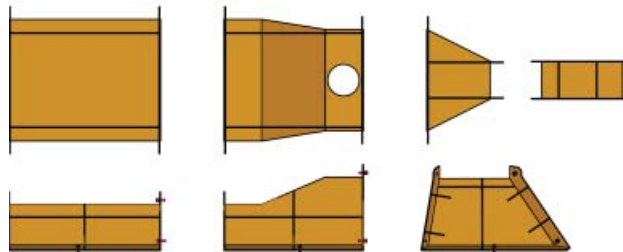
Breakdown of unique parts within the formwork.



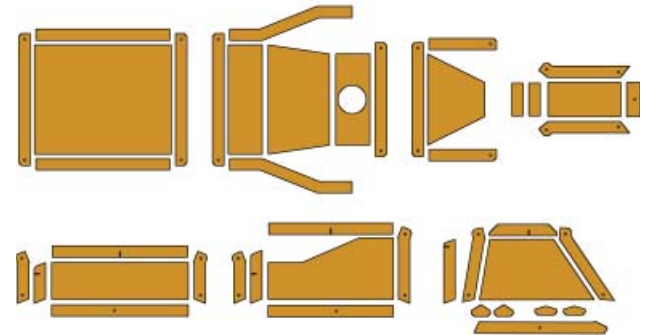
Exploded sub-assemblies



7 unique sub-assemblies



7 unique sub-assemblies

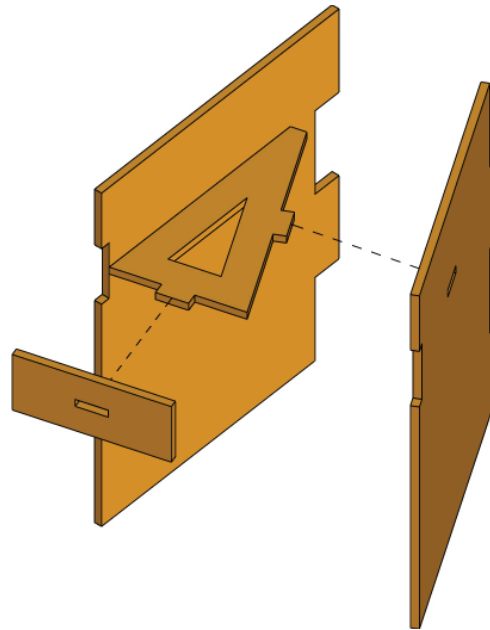


Composed of 44 parts (some common)

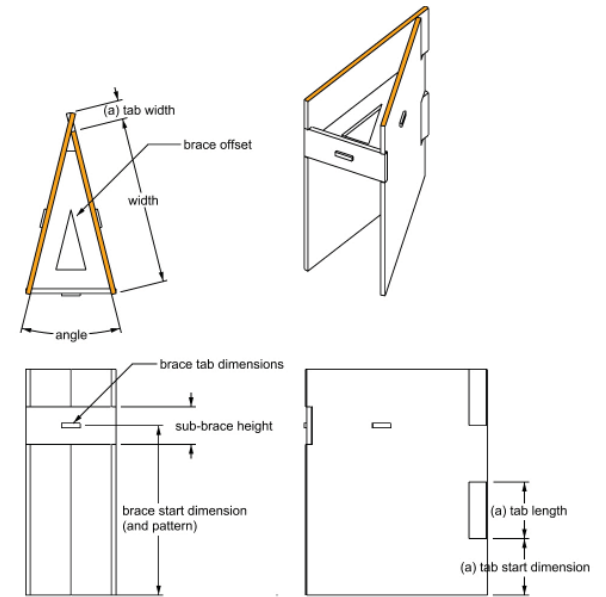
Scale 1

There is the potential to explore new section types with different performative and aesthetic properties. These sections can relate more intimately to the overall design of a structure. For example, a three-way radial section can conform to the angles in a hexagonal structural bay, or be implemented as a four-way radial section for orthogonal bays.

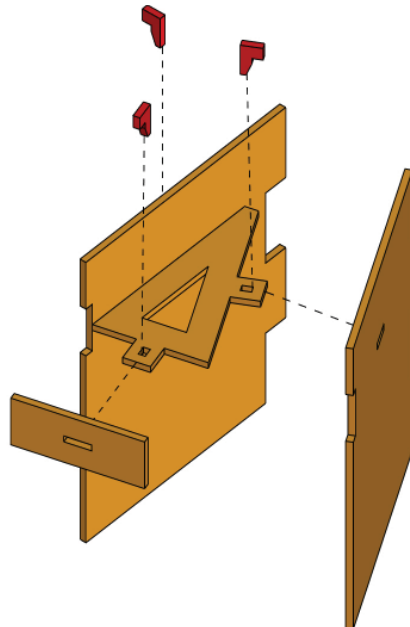
A triangular section was the first alternative, followed by a radial section.



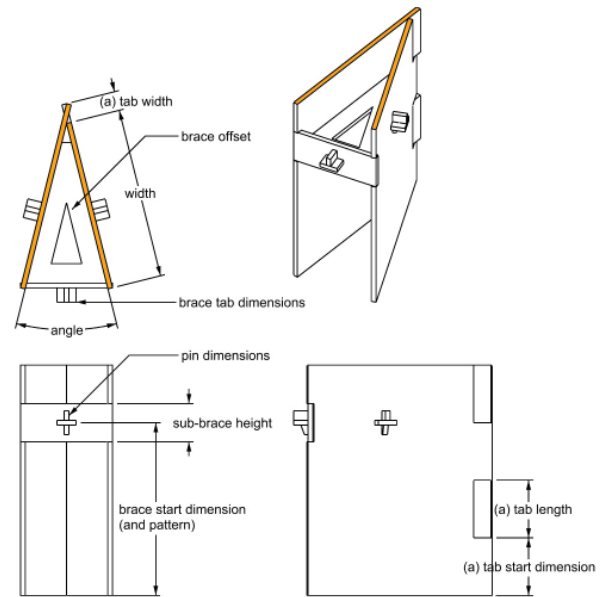
Welded section



Parameters



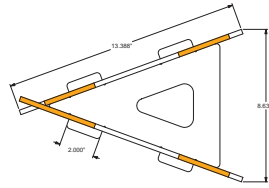
Mechanically-secured section



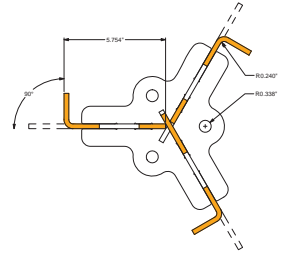
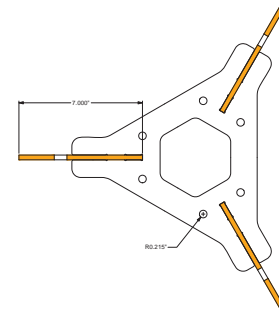
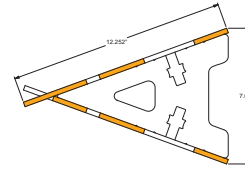
Parameters

Scale 1

Far left: Triangular section, fixtured with a spinal comb joint and slot and tabbed perpendicular plates. The tabs are extended to facilitate fillet welds. The webs exhibit variable depth.

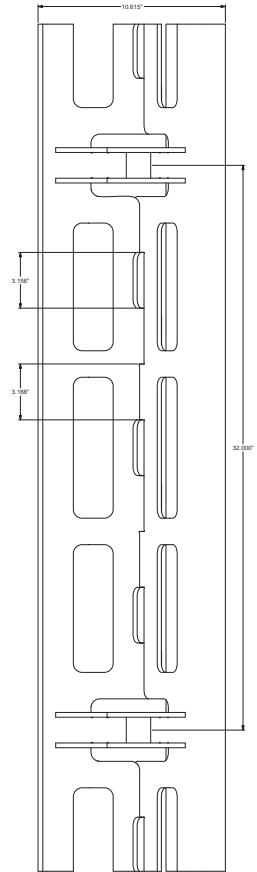
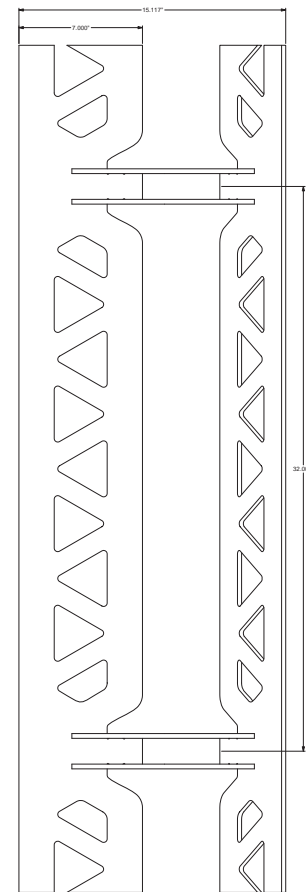
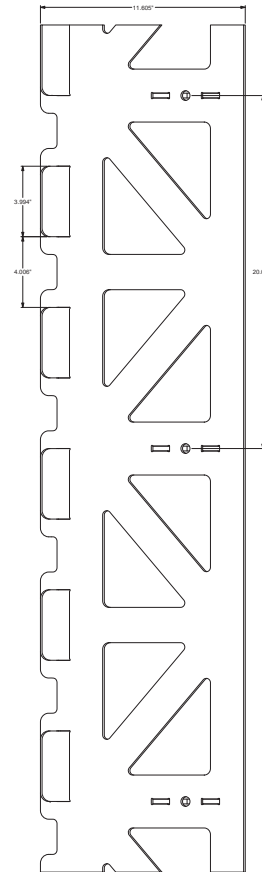
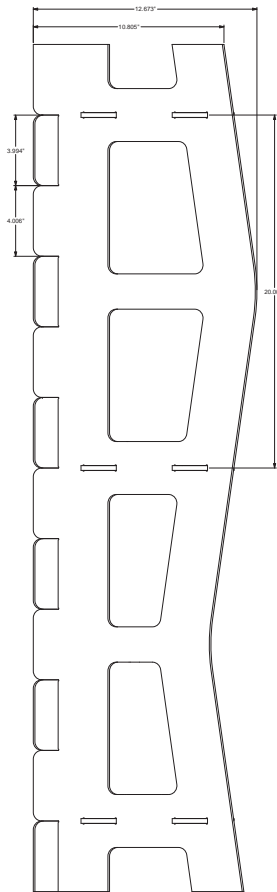


Left: Triangular section, fixtured with a spinal comb joint and slot and tabbed perpendicular plates. The plates accommodate nuts for bolted connections.

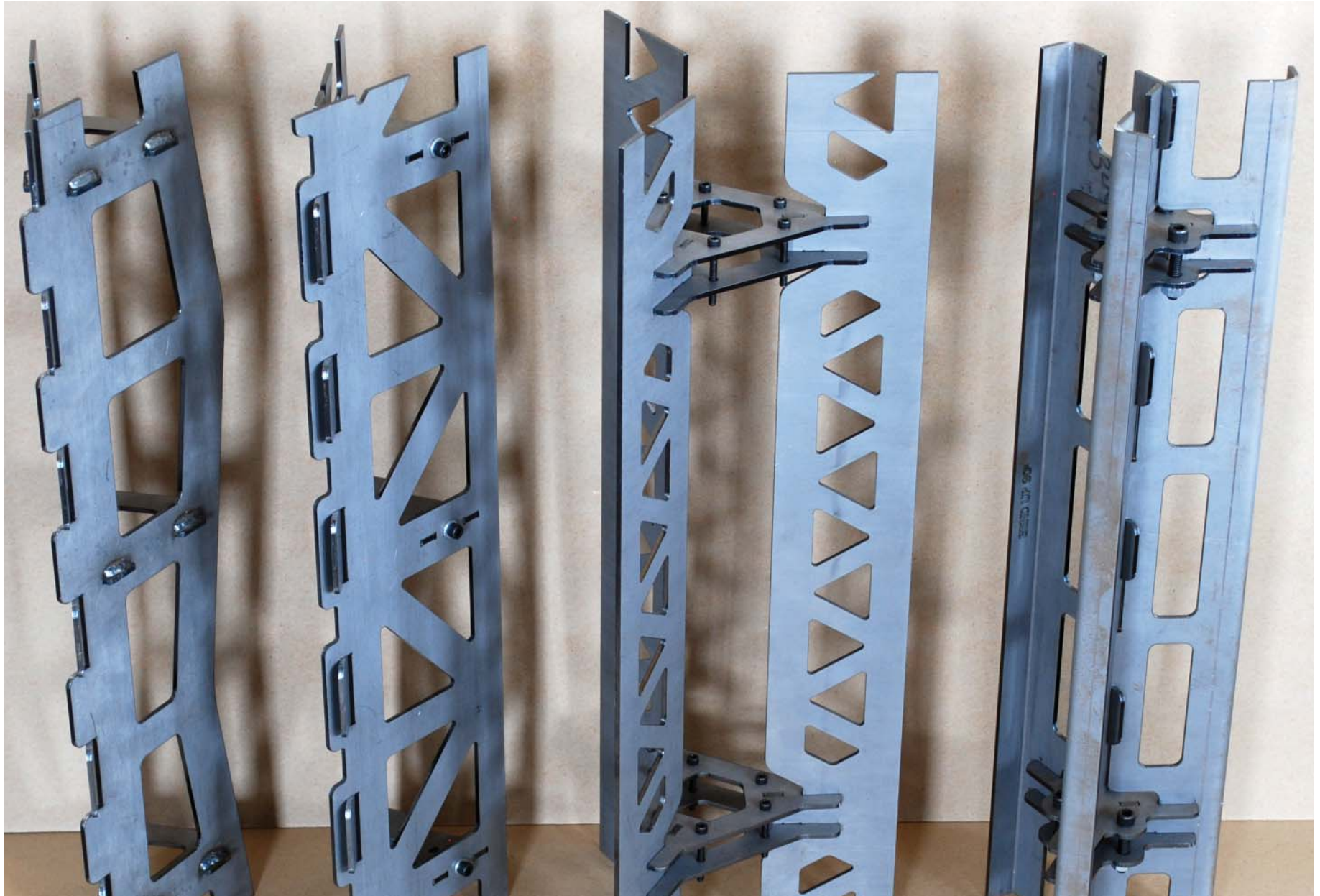


Right: Radial section (three-way), fixtured with slot and tabbed bolted plates.

Far right: Radial section (three-way), fixtured with slot and tabbed bolted plates, three-way comb joint, and reinforced with bent edge flanges.



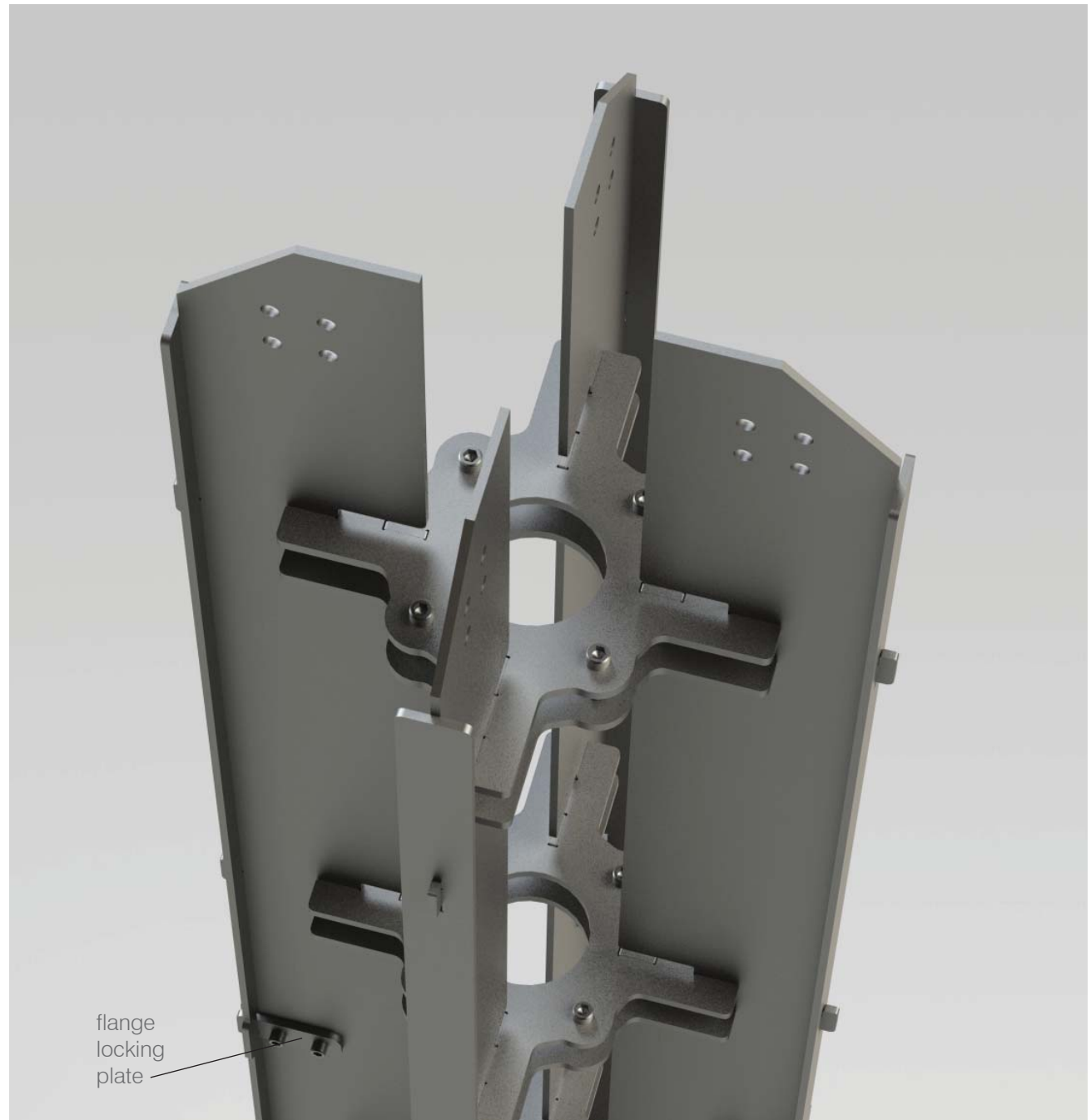
Scale 1



Scale 1 beam/column prototypes

Scale 1

Radial section (four-way), fixtured with slot and tabbed bolted plates, and reinforced with slide-locked edge flanges. The four-way, non-comb joint section is a selected for use as a column so that drainage pipe can be routed through the center. The idea of using a bent edge flange was abandoned as it was decided that the individual webs would be too long and heavy to bend in conventional metal bending setups. Instead, a separate edge flange plate is attached to the web utilizing scale 0 slide-lock slot and tab connections, which are secured via small bolted plates that lock in the opposite direction. These flanges secure the web against buckling at regular intervals, increasing the column's resistance against compression and torsion.

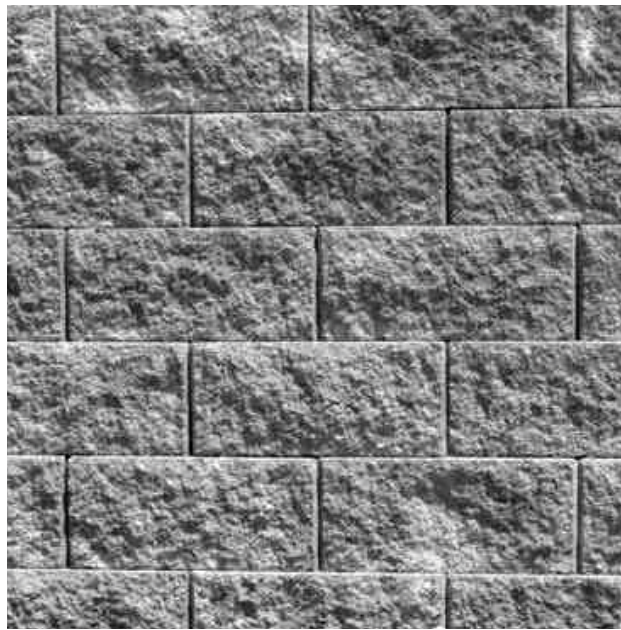


Scale 1 column assembly

Scale 1 Masonry

Gas stations often embody a non-relationship between the canopy and convenience store. In the case of a highly tectonic, mechanistic canopy, a stereotomic convenience store can create an antagonistic relationship, serving to emphasize each component of the design.

Searching for a self-fixturing alternative to the basic CMU lead to a high insulation performance, self-fixturing concrete unit. This unit is based upon existing precedents and maintains the pragmatic aesthetic of the CMU. Conversely, it conceals internal insulation, allowing both faces to express the “authentic” quality of concrete, while also expressing the nature of the block as a multi-part assembly through the revealed bolts.



Stereotomic contrast to tectonic canopy



Precedent: self-fixturing, dry-stack masonry units (Firth EsiBloc Mortarless Masonry)



Precedent: foam-insulated concrete assembly (Solarcrete insulated concrete wall system)



Masonry unit sub assembly

Scale 2 & 3

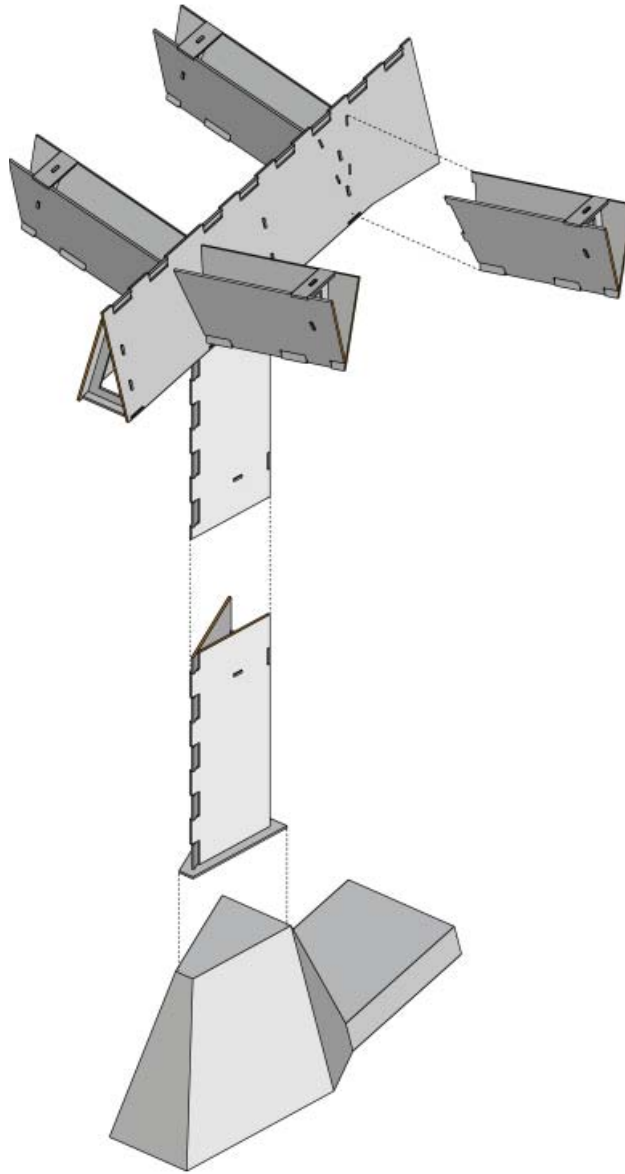
These assemblies join Scale 1 sub-assemblies (beams and columns) to form a prototypical gas station canopy section. The Scale 1 units are either shipped to the site in a flat-pack configuration or pre-assembled in a shop. Regardless, all parts hold and self-locate, and also serve to fixture additional elements, such as slots in the flanges to locate interstitial elements such as purlins (not shown), or a ring in columns through which to channel conduit, drainage, etc.



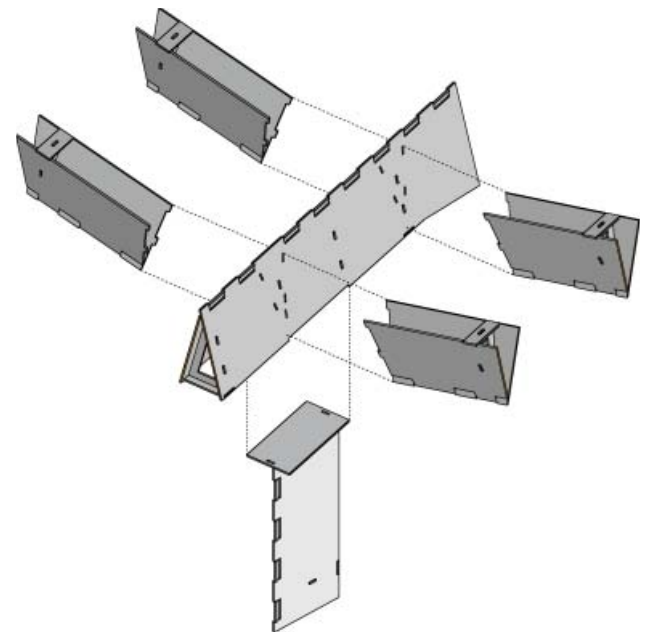
Scale 2 structural prototypes

Scale 2

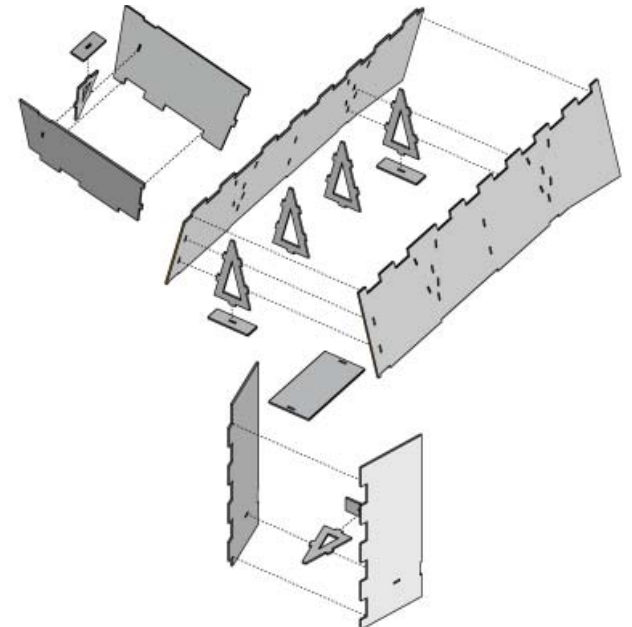
An assembly based upon the triangular section. All connections are welded in this example.



Assembled components



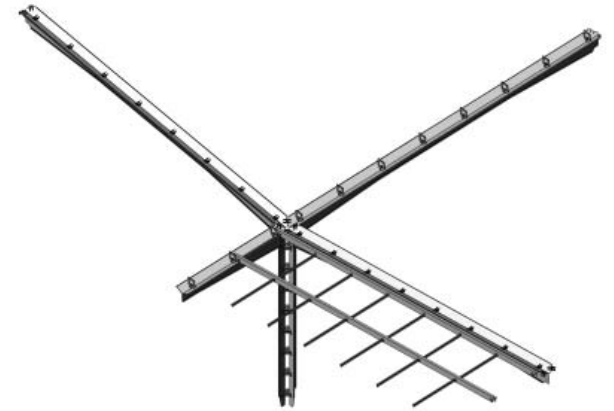
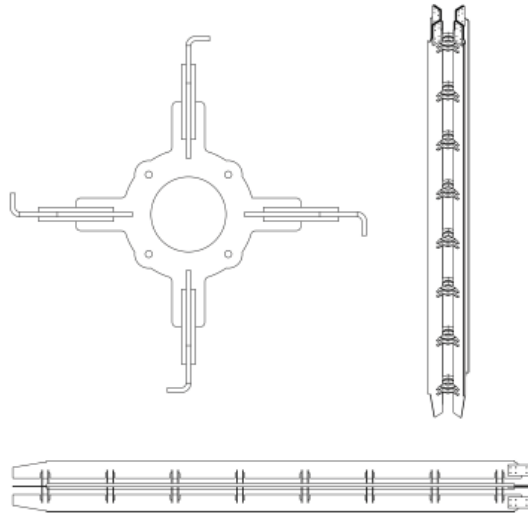
Assembly of Scale 1 sub assemblies



Scale 0 connections with Scale 1 sub assemblies

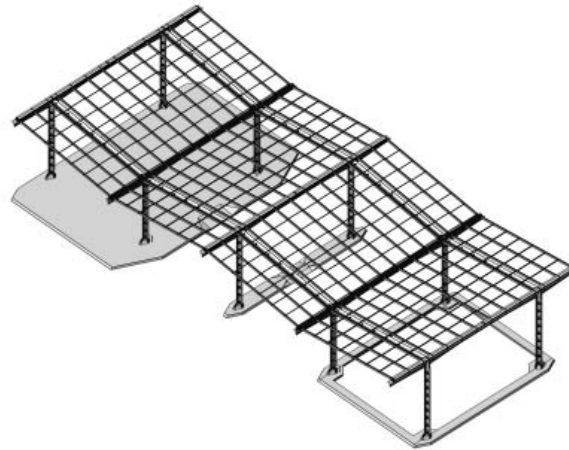
Scale 2 & 3

An assembly based upon the four-way radial section. All connections are bolted in this example.



Scale 1 column

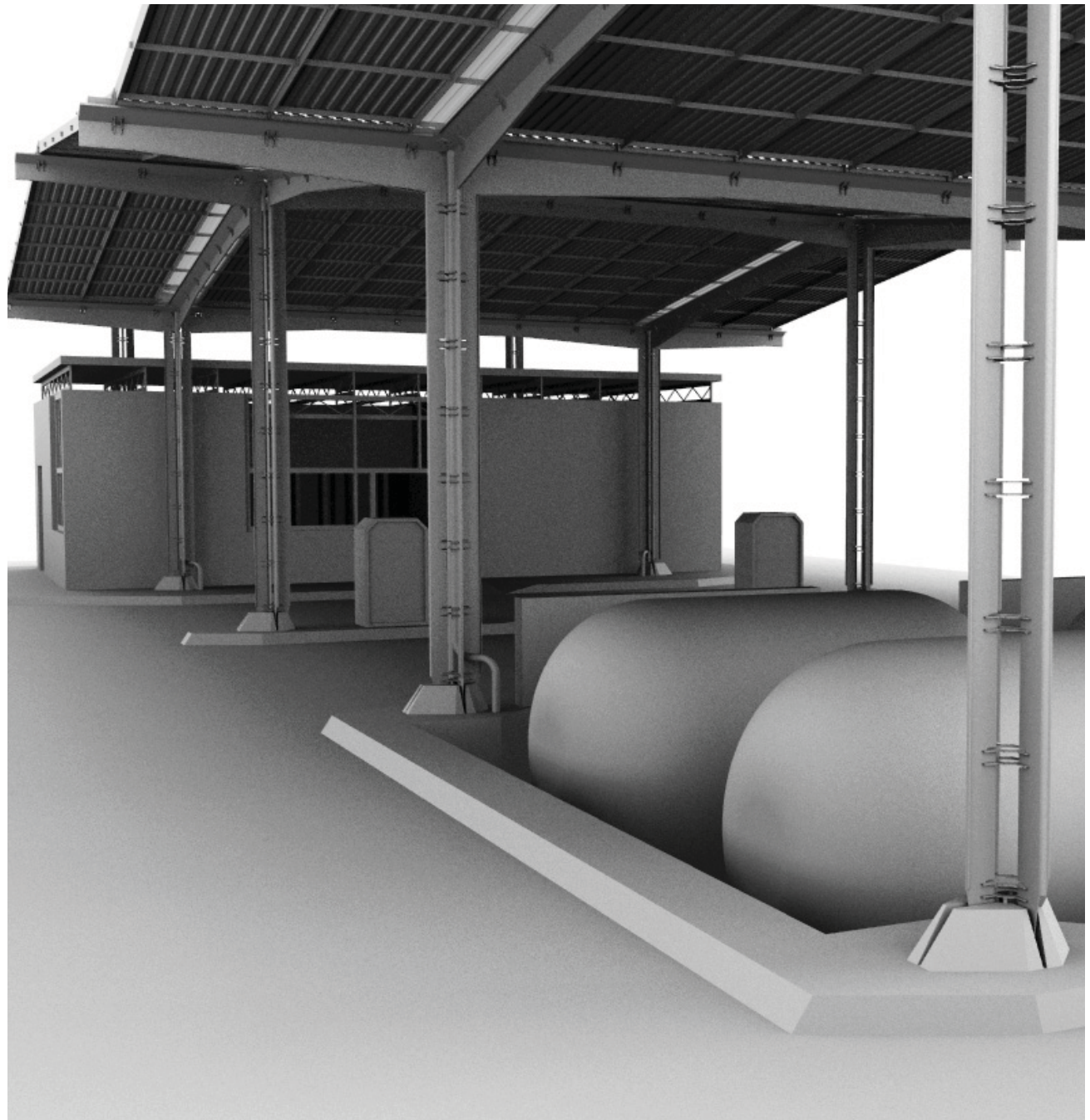
Scale 2 assembly



Scale 3 assembly

Scale 3

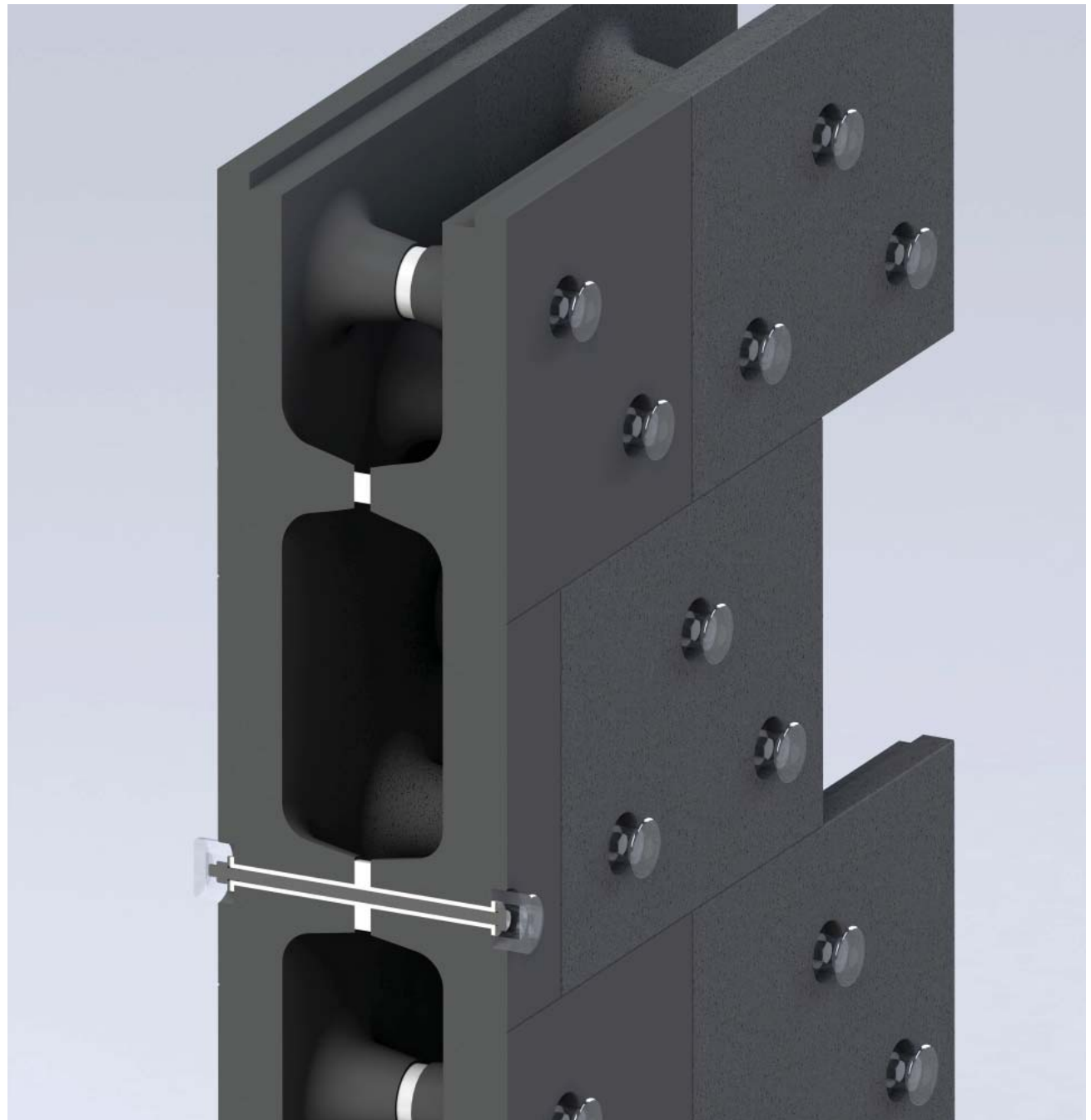
The Scale 2 conditions are extrapolated in a Scale 3 schematic genotype.



Schematic gas station genotype

Scale 2 Masonry

A typical wall assembly is composed of multiple high performance, self-fixturing sub assemblies.

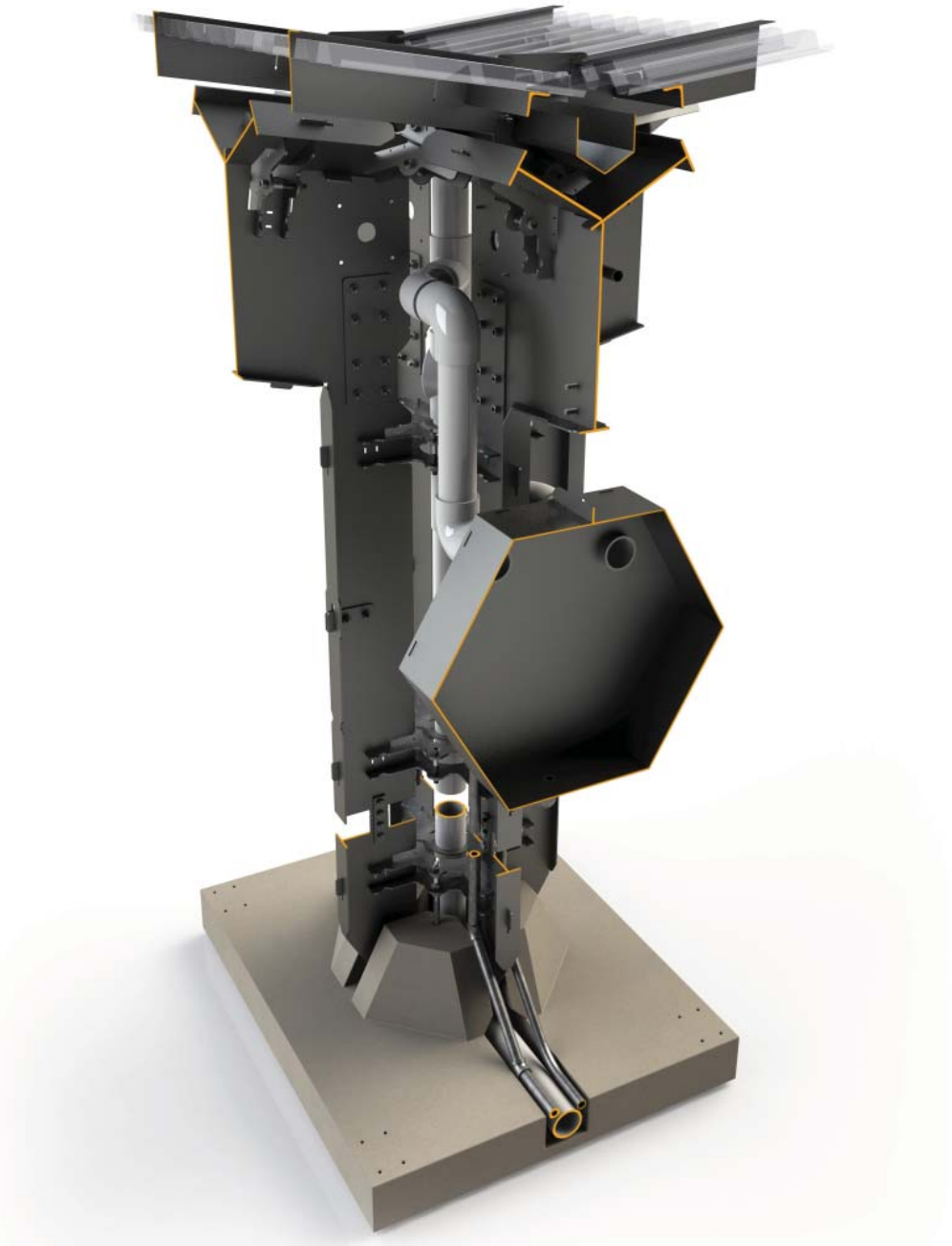


Wall composed of masonry units

Prototype

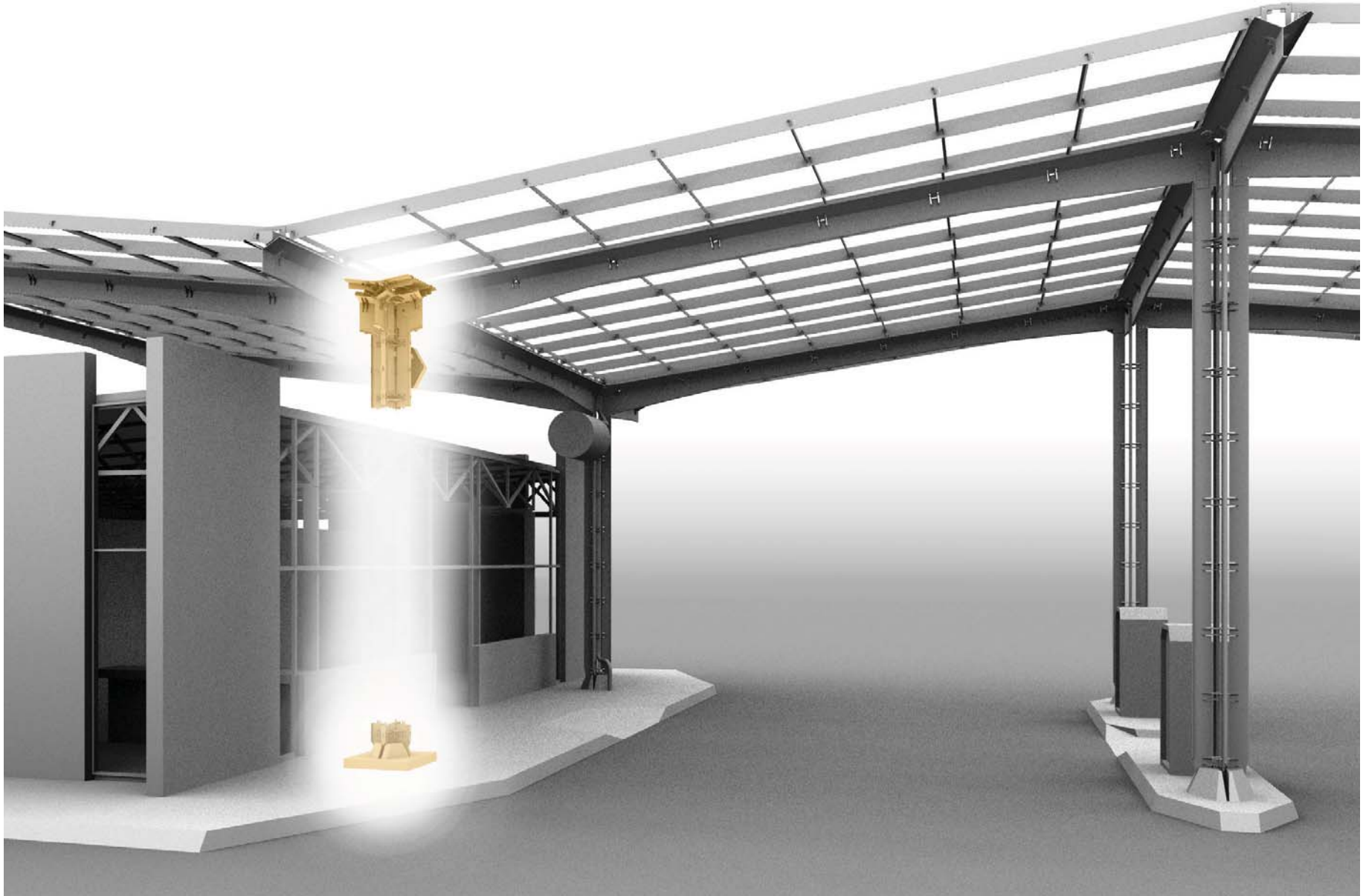
The prototype is essentially an intense exploration of a Scale 2 condition. It employs Scale 1 sections that have been determined to be the most appropriate fit for a self-fixturing gas station. These Scale 1 sections include the radial (three-way) beam with comb-joints and the radial (four-way) column. Both beams and columns include locking flange parts, compression plates, and numerous locations to be used in the fixturing of additional systems. In this way, the structural prototype acts as an armature for systems. The aesthetic intent relies heavily on the detail-up design process, where considerations such as fillets and tolerances govern the assembly, and the expression of fixturing and systems is the primary goal.

The primary system is water drainage. The roof routes water into a bent gutter, which feeds a drainage pipe that runs down the center of the column into the cast-in-place footing for disposal via the storm sewer. A valve allows the water to be routed into a catchment tank during non-freezing conditions, where it is stored and then fed down a galvanized water pipe into the convenience store for graywater usage. Owing to the elevated location of the tank, there is gravity-fed water pressure. Overflow in the tank goes down the central drainage pipe. Electrical conduit is also fixtured in the assembly. System fixturing points are present throughout such that parts tend to be symmetrical, reducing installation issues, allowing systems to be installed indiscriminately, and creating a visual motif.



Prototype render, section cuts highlighted in orange

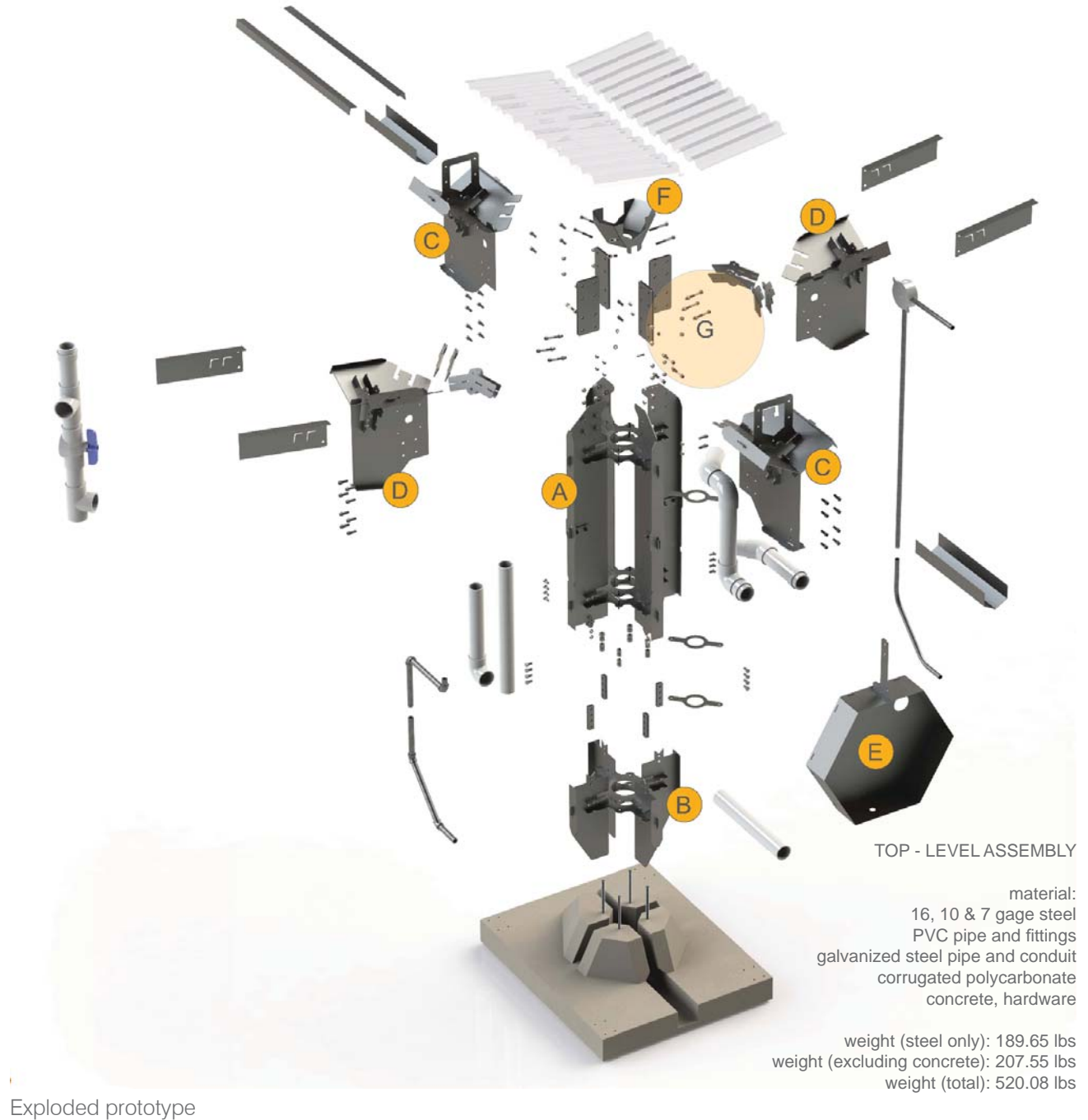
Prototype Location



Location of prototype within context of schematic genotype

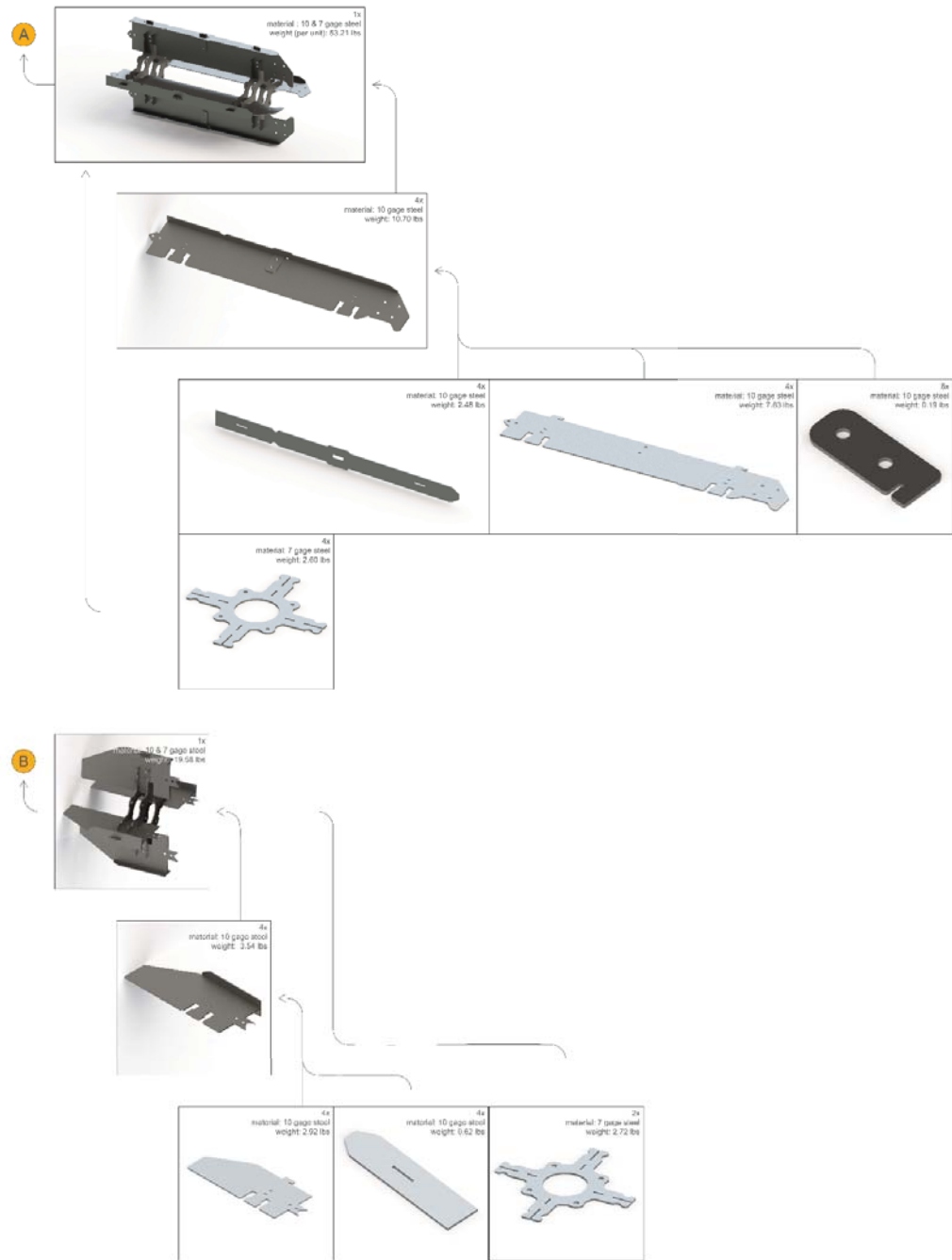
Prototype Assembly

The assembly is shown exploded into its sub assemblies, fasteners, cast-in-place foundation, and systems. The letters designate either a sub assembly or group of parts, all of which are composed of digitally fabricated, self-fixturing, laser cut steel. Each lettered sub assembly is further shown as a collection of small sub assemblies and finally unique parts.



Prototype Assembly

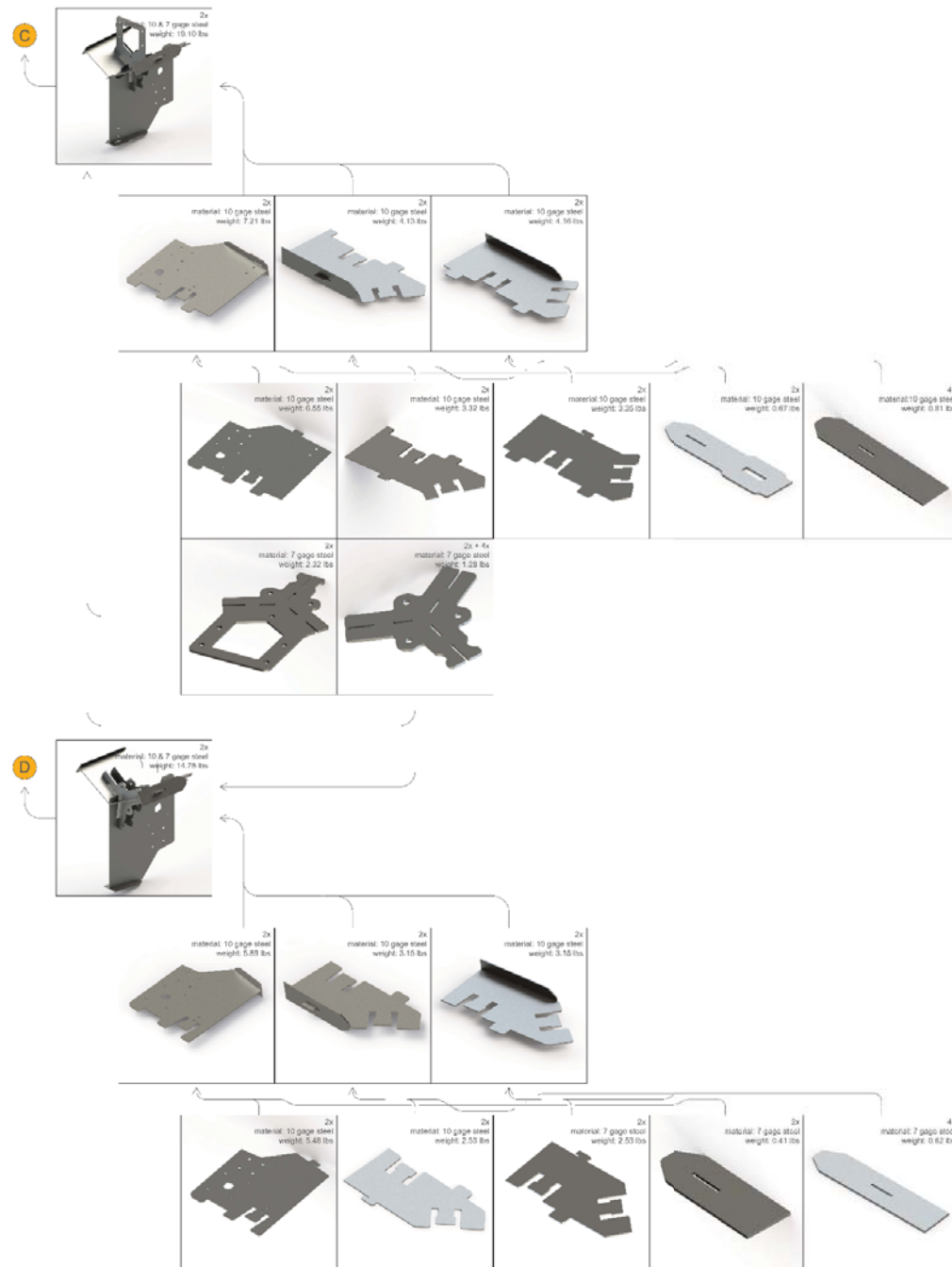
Sub assemblies A and B represent a section-cut column (at 1:1, the column would be approximately 17 feet tall as opposed to a more manageable 52 inches).



Sub assemblies A and B

Prototype Assembly

Sub assemblies C and D are section-cut portions of the beams. There are two of each. Beam C connects an adjacent column horizontally, while beam D connects an adjacent column at an angle in order to facilitate drainage into the gutter, which is nested within beam C.



Sub assemblies C and D

Prototype Assembly

Sub assembly E is a section-cut gray water storage tank. The tank is welded. The tank features an inlet for rain water, and outlet for excess water, and a bottom drain to supply the gravity-pressurized gray water line.

Sub assembly F is another welded component, with the purpose of routing water from the gutters into the roof drain pipe.

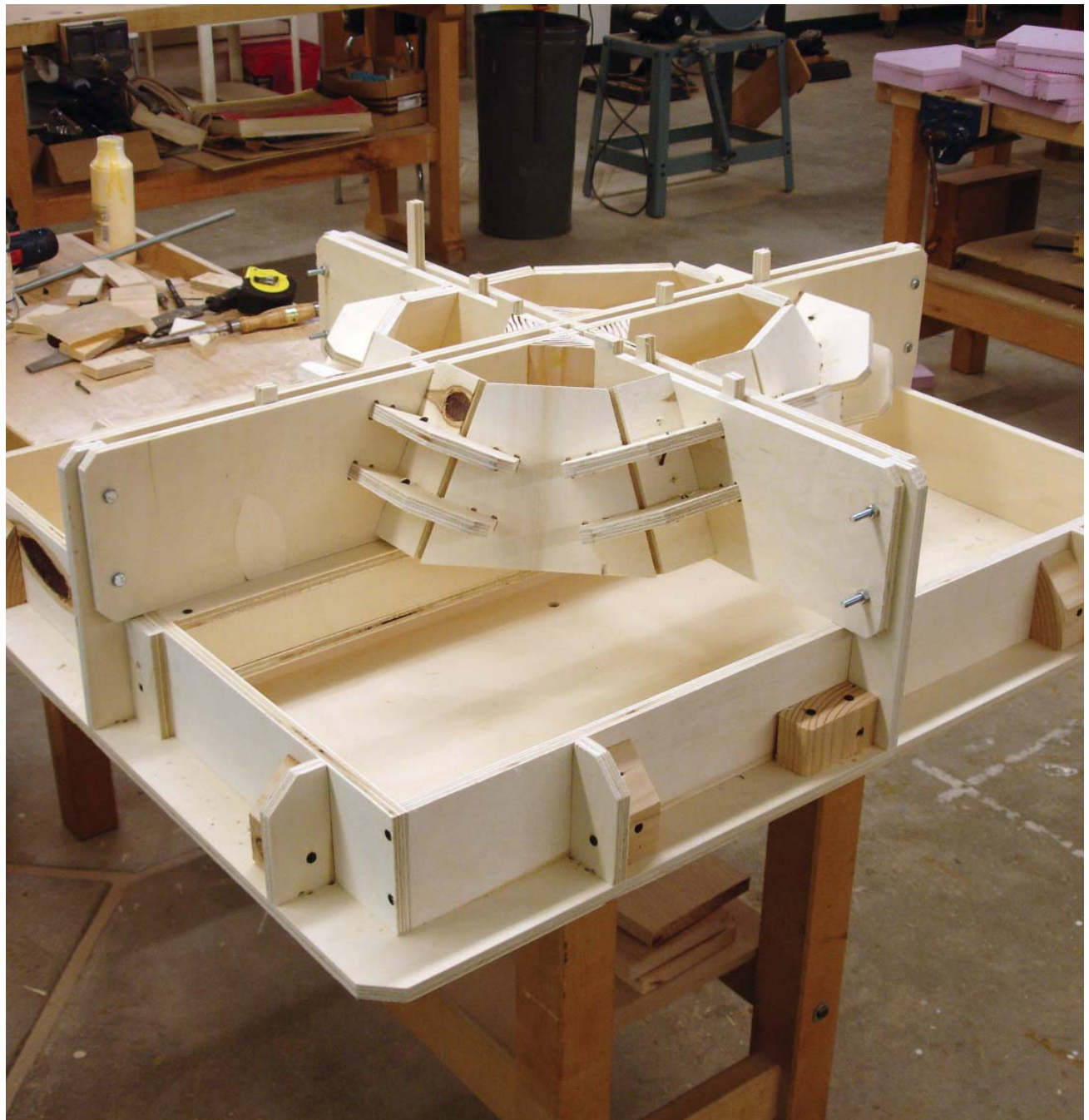
The final group of parts are installed directly at the top-level of the prototype as opposed to be composed of smaller sub assemblies themselves.



Sub assemblies E and F, part group G

Prototype

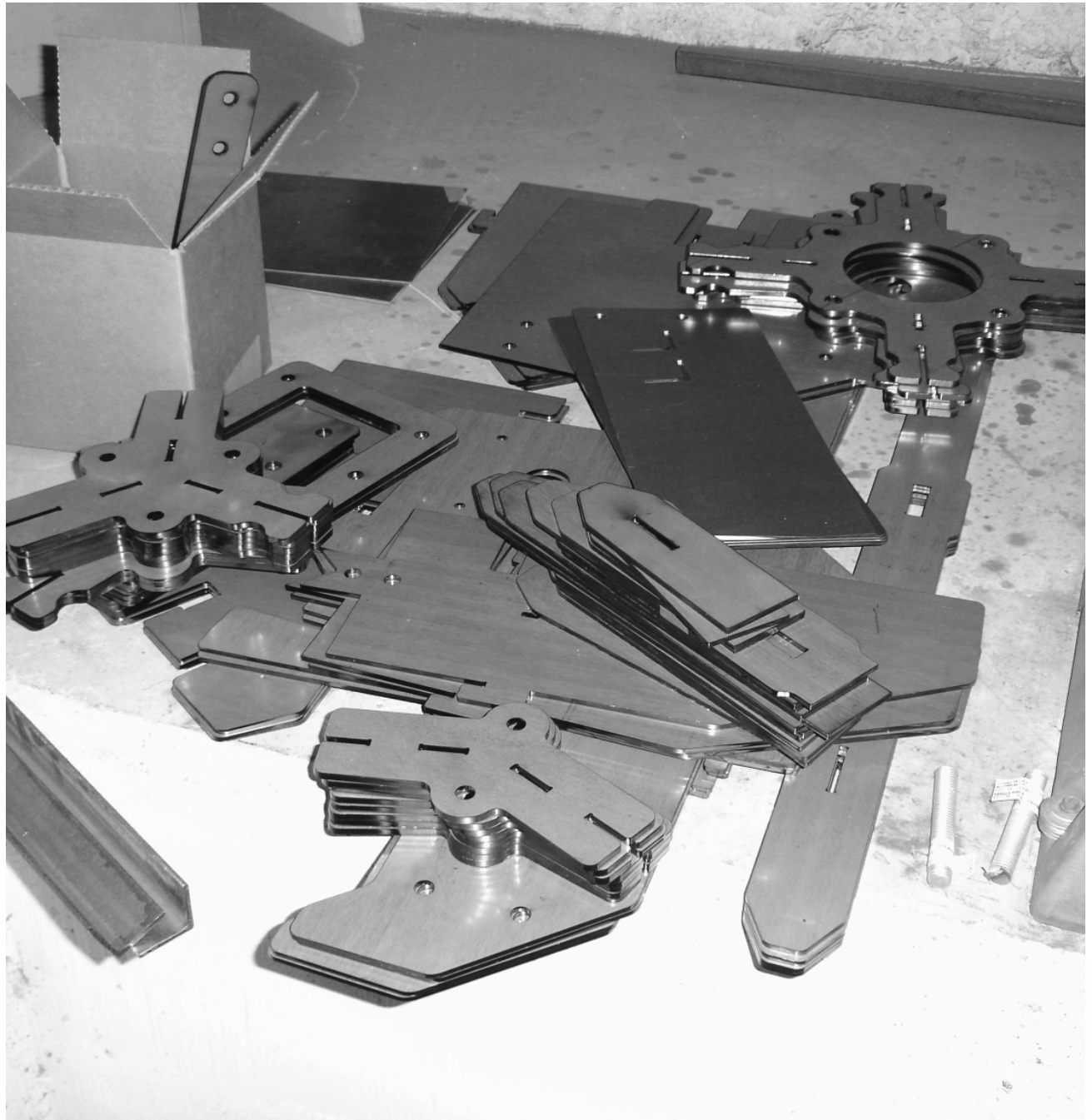
The cast-in-place concrete formwork was based upon earlier self-fixturing formwork exercises. The formwork was CNC-routed from 1/2" plywood. The parts were also designed to be self-fixturing.



Formwork

Prototype

Approximately 200 pounds of steel parts take up very little volume when moved in flat format.



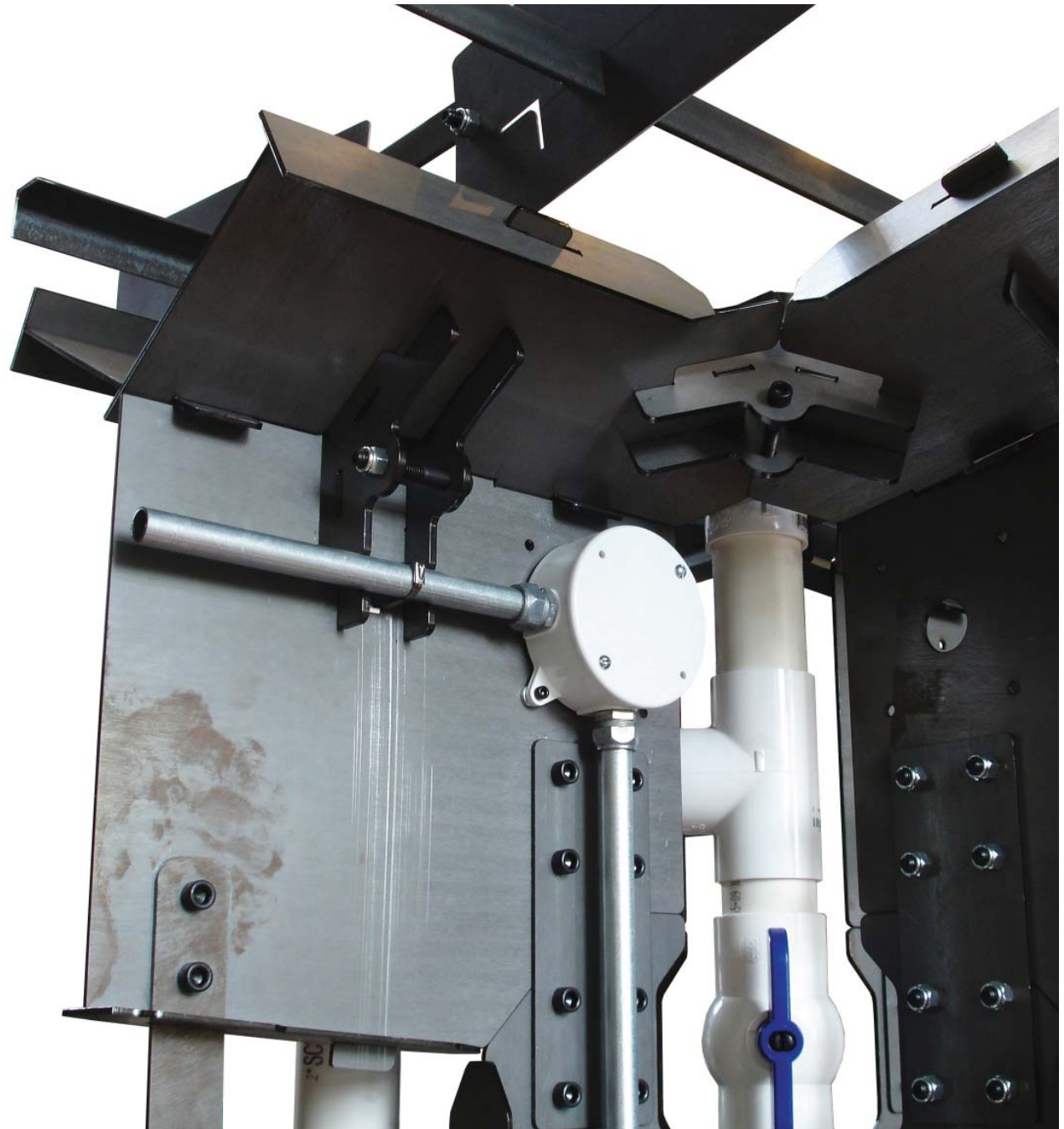
Laser-cut steel parts

Prototype

The finished physical prototype. All systems are located, notably the electrical conduit and junction box, which take advantage of a recessed semi-circle and pre-cut holes, respectively.

Not all systems fixturing locations are utilized. This allows additional systems to be installed later, and means that sub assemblies can be installed in a variety of orientations. For example, the column could be rotated 90 degrees with respect to the beams and still provide locating and holding features for the electrical system, as every web is identical. Correlated with this is the attempt to use semi-universal parts, which improves production economy. Ubiquitous fixturing also reduces the potential for installation errors.

Additionally, extra fixturing locations create a visual motif expressing the aesthetic of function. If unused, these features are pragmatically superfluous, yet express the aesthetic of function. As a motif, they arguably depict the future potential for function, while all of the utilized fixturing locations express the past application of fixturing.



Laser-cut steel assembly

Prototype



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